Landscape connectivity and Remote Sensing applications for assessing biodiversity patterns in desert environments

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NOTA PRÉVIA

Na elaboração desta tese, e nos termos do número 2 do Artigo 4o do Regulamento Geral dos Terceiros Ciclos de Estudos da Universidade do Porto e do Artigo 31º do D.L. 74/2006, de 24 de Março, com a nova redação introduzida pelo D.L. 230/2009, de 14 de Setembro, foi efetuado o aproveitamento total de um conjunto coerente de trabalhos de investigação já publicados ou submetidos para publicação em revistas internacionais indexadas e com arbitragem científica, os quais integram alguns dos capítulos da presente tese. Tendo em conta que os referidos trabalhos foram realizados com a colaboração de outros autores, o candidato esclarece que, em todos eles, participou ativamente na sua conceção, na obtenção, análise e discussão de resultados, bem como na elaboração da sua forma publicada.

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RESUMO

A conectividade da paisagem reduz o isolamento das populações e permite a dispersão de indivíduos para áreas climaticamente mais favoráveis. Avaliar os padrões de conectividade da paisagem em ambientes desérticos pode constituir uma prioridade para a conservação dessas áreas. A Detecção Remota (DR) tem demonstrado ser uma ferramenta eficiente em estudos focados em ecologia, distribuição da biodiversidade e conservação, dado o seu poder em detectar factores-chave do estado e da alteração da biodiversidade global. A DR também fornece representações efectivas da estrutura da paisagem, o que constitui uma fonte de informação significativa para melhorar os estudos de conectividade da paisagem. Estas técnicas são particularmente úteis para estudar padrões de biodiversidade em regiões extremamente remotas, como os desertos e as regiões áridas, áreas que dificultam a investigação de campo.

A biodiversidade global enfrenta actualmente perdas severas e muitas espécies estão em vias de extinção. As alterações climáticas e a fragmentação de habitats representam dois dos maiores factores indutores da perda de biodiversidade. Estes impactos são normalmente exacerbados em regiões extremas, como em desertos e zonas áridas. Estas regiões são vistas frequentemente como zonas naturalmente pobres e homogéneas, embora abriguem biodiversidade única e frágil a necessitar de atenção global. Por exemplo, o Saara-Sael suporta muitas espécies endémicas e populações faunísticas relíquia com diferentes origens biogeográficas, como o crocodilo da África Ocidental (*Crocodylus suchus*). As populações relíquia do Saara estão sujeitas a efeitos de isolamento extremo e estão profundamente expostas a oscilações climáticas extremas.

Por estas razões, o objectivo principal desta tese é o de verificar qual a importância da conectividade da paisagem para os organismos desérticos e como é que as avaliações de padrões de biodiversidade podem ser beneficiadas através da aplicação de ferramentas de DR. Concretamente, foram delineados quatro alvos cruciais para atingir este objectivo principal: 1) Avaliar o estado actual dos métodos de conectividade estrutural para aplicações em ecologia, evolução e conservação; 2) Testar as contribuições potenciais da DR na avaliação de padrões de distribuição da biodiversidade em zonas áridas globais; 3) Identificar e mapear com detalhe importantes componentes da paisagem para a consequente avaliação de padrões de biodiversidade local no Oeste do Saara-Sael; 4) Analisar a distribuição e os efeitos das oscilações

climáticas na estrutura e conectividade populacional dos crocodilos da África Ocidental no Saara-Sael.

Para atingir o primeiro alvo, foi elaborada uma revisão que inclui conceitos teóricos base e uma lista de vantagens e desvantagens dos métodos de conectividade estrutural. Esta revisão foca-se nos métodos insuficientemente revisados e nos desenvolvimentos metodológicos mais recentes para medir a conectividade estrutural. Adicionalmente, são dadas intuições sobre a aplicabilidade destes métodos em ecologia, evolução e conservação, e as futuras direcções a tomar para melhorar os estudos da conectividade da paisagem são também discutidas. Estudos futuros da conectividade da paisagem deverão focar-se no desenvolvimento de abordagens integrativas. Isto poderá ser conseguido através da incorporação de métodos/outputs complementares que contribuirão para melhorar a compreensão de relações espécie-paisagem a níveis estruturais e funcionais. O aumento de esforços no desenvolvimento de recursos computacionais e recolha de dados (e.g., dados de genética e de movimento) permitirão o emprego de métodos sofisticados para avaliar a conectividade populacional e para preservar padrões de conectividade da paisagem.

Para responder ao segundo objectivo, foram avaliados os bio-indicadores de DR de maior utilidade para descrever os padrões de distribuição de vertebrados terrestres em zonas áridas. Vinte e sete bio-indicadores (médias e variabilidade inter-anual de estimativas de produtividade primária líquida, precipitação, humidade do solo, eficiência do uso da chuva e eficiência do uso da humidade do solo, agregadas sazonalmente) derivados de dados MERIS ao abrigo do Projecto Diversity II da Agência Espacial Europeia, são usados para prever riquezas funcionais de 739 espécies de vertebrados terrestres, distribuídos ao longo de cinco zonas áridas globais. Variáveis derivadas de DR relacionadas com a disponibilidade de água, particularmente com a precipitação e humidade do solo, revelaram relações mais próximas com as riquezas específicas (para ambas as riquezas totais e funcionais) de vertebrados na maioria das zonas áridas avaliadas, em comparação com as estimativas de produtividade primária, eficiência do uso da chuva e eficiência do uso da humidade do solo. As relações mais fortes foram observadas entre os indicadores de disponibilidade de água e os padrões de distribuição de espécies de vertebrados de pequeno tamanho corporal (particularmente anfíbios).

Para concretizar o terceiro objectivo, foi derivado um mapa do coberto do solo do Oeste do Saara-Sael (com 30x30 m de resolução), com base numa metodologia passo-a-passo de avaliaçao do coberto do solo. Para isso, pontos de controlo-GPS com traços descriptivos detalhados do coberto do solo foram usados em classificações de imagens de satélite Landsat. Foi obtida uma classificação regional do coberto do solo robusta

(83.9% de pontos correctamente classificados) para o Oeste do Saara-Sael, principalmente para as regiões mais áridas. O mapa final é composto por 18 classes e poderá ser usado em mapeamentos de distribuições de biodiversidade locais e para melhorar a eficiência de acções de conservação locais e gestão de recursos naturais para as comunidades locais.

Foram desenvolvidos dois trabalhos para concretizar o último objectivo. Primeiro, foi conduzida uma actualização da distribuição, habitats ocupados, tamanhos populacionais e factores de ameaça de *C. suchus* na Mauritânia. Os dados recolhidos durante cinco expedições de campo à Mauritânia (2011-2016) permitiram descobrir várias localidades novas com crocodilos (N=26), aumentando em 27% o actual número de localidades conhecidas. Foram identificados vários factores de ameaça que afectam as populações de crocodilos e os seus habitats (N=11). Os factores frequentemente detectados foram a seca e temperaturas extremas (100% das localidades afectadas) e a extracção de água para uso doméstico e pastagem nómada (94%). As populações de crocodilos estão aparentemente ameaçadas, concretamente as que se encontram no extremo norte da Mauritânia (montanha do Tagant), sendo necessário um planeamento de estratégias de conservação local para assegurar a persistência das frágeis populações de crocodilos. Segundo, foi efectuada uma avaliação do papel das oscilações climáticas na conectividade da paisagem, nos padrões genéticos e na dinâmica de dispersão do *C. suchus*, a nível espacial e temporal. Foram medidas estimativas de diversidade genética, estrutura populacional e fluxo de genes de crocodilos adultos e juvenis, e foram avaliados cenários históricos (1980s) e contemporâneos (2010s) de conectividade da paisagem, de forma a verificar se os padrões genéticos das populações de crocodilos estão correlacionados com agentes climáticos indutores da conectividade. Os crocodilos apresentam níveis mais elevados de isolamento a norte da Mauritânia, em comparação com as populações do sul da região, indicando possíveis efeitos de isolamento por distância.

Esta tese demonstrou com sucesso a importância da conectividade da paisagem para os organismos do deserto e também como as avaliações de padrões de biodiversidade podem ser melhoradas com a utilização de ferramentas de DR. Aproximações interdisciplinares, como o exemplo apresentado nesta tese, em que se se combinam métodos de conectividade da paisagem/técnicas de DR/análises genéticas para avaliar a conectividade populacional local do crocodilo da África Ocidental, são fortemente recomendadas para o suporte de estratégias de conservação sólidas, principalmente em áreas negligenciadas e ricas em biodiversidade como os ambientes desérticos.

PALAVRAS-CHAVE: Distribuição da biodiversidade; Conservação da biodiversidade; Indicadores de biodiversidade; Oscilações climáticas; Ambientes desérticos; Zonas áridas; Corredores hidrográficos; Coberto do solo; Conectividade da paisagem; Mauritânia; Montanhas; Populações relíquia; Detecção Remota; Saara; Sael; Conectividade estrutural; Habitats aquáticos; Crocodilo da África Ocidental; Oeste do Saara-Sael.

SUMMARY

Landscape connectivity reduces population isolation and allow dispersal of individuals to areas with favourable climatic conditions. Assessing landscape connectivity patterns in desert environments may constitute a major priority for future conservation planning in those areas. Remote Sensing (RS) has proven to be an effective tool for studies focused in ecology, biodiversity distribution and conservation, given its power in detecting key drivers of biodiversity status/change across the globe. Also, RS provides effective representations of the landscape structure, which constitutes a significant source of information for improving landscape connectivity studies. These techniques are particularly useful for studying biodiversity patterns in extremely remote regions, such as such as deserts and arid regions, where field investigations are difficult to perform.

Global biodiversity is currently facing severe losses and many species are on the brink of extinction. Climate change and habitat fragmentation represent two major factors enhancing the catastrophic degradation of biodiversity worldwide. These impacts are normally exacerbated in extreme regions, such as deserts and arid regions. These regions are frequently regarded as naturally poor and homogenous regions, although comprising unique and fragile biodiversity in need of global attention. For instance, the Sahara-Sahel holds many endemics and relict faunal populations with different biogeographical origins, such as the West African crocodile (*Crocodylus suchus*). Saharan relict populations are subjected to effects of extreme isolation and are deeply exposed to extreme climatic oscillations.

Accordingly, the main objective of this thesis is to verify the importance of landscape connectivity for desert organisms and how current assessments of biodiversity patterns in desert environments can profit from the application of RS tools. Concretely, four crucial goals were delineated in order to achieve this principal objective: 1) Evaluate the current state of structural connectivity methods for application in ecology, evolution and conservation; 2) Attest potential contributions of RS to the assessment of biodiversity distribution patterns in global drylands; 3) Identify and map in detail important landscape features for the assessment of local biodiversity patterns in the West Sahara-Sahel; 4) Analyse the distribution and the effects of climatic oscillations on population structure and connectivity of West African crocodiles in the West Sahara-Sahel.

For achieving the first goal, it was developed a review encompassing basal theoretical concepts and listing major advantages and disadvantages of structural connectivity methods. This review is focused on insufficiently reviewed methods and on the most recent methodological developments for measuring structural connectivity. Additionally, insights concerning the applicability of these methods in ecology, evolution and conservation are provided, and future directions for improving landscape connectivity studies are also discussed. Future landscape connectivity studies should focus on the development of integrative frameworks. This may be accomplished by incorporating complementary methods/outputs that will improve our understanding of species-landscape relationships at structural and functional levels. Increased efforts on the development of computational resources and on data collection (e.g., genetic and movement data) will allow the employment of sophisticated methods to evaluate population connectivity and the preservation of landscape connectivity patterns.

For answering to the second goal, it was performed an assessment of the most useful RS bio-indicators for describing terrestrial vertebrate distribution patterns in drylands. Twenty seven bio-indicators (averages and inter-annual variability of seasonally aggregated proxies for net primary production, rainfall, soil moisture, rain use efficiency, and soil moisture use efficiency) derived from MERIS data under the European Space Agency - Diversity II Project are used to predict functional species richness of 739 terrestrial vertebrates distributed across five global drylands. RS-derived variables related to water availability, particularly precipitation and soil moisture, reveal closer relations with vertebrate species richness (both total and functional richness) in most of the analysed drylands, in comparison to estimates of primary productivity, rain-use efficiency and soil moisture-use efficiency. The strongest relations are observed between water availability indicators and distribution patterns of vertebrate species with small body size (particularly amphibians).

To accomplish the third goal, it was derived a land cover map of the West Sahara-Sahel (30x30 m resolution) based on a stepwise methodology for land cover assessment. A collection of GPS control points with detailed descriptive traits were used for Landsat image classification. A robust regional classification (83.9% points correctly classified) of land cover is obtained for the West Sahara-Sahel, particularly for the most arid regions. The final map is composed by a total of 18 classes, and might be used for mapping local biodiversity distribution and for improving the effectiveness of local conservation actions and management of natural resources for local communities.

Two works are developed to accomplish the last goal. Firstly, an update of the distribution, occupied habitats, population size, and threat factors of *C. suchus* in Mauritania is conducted. Data collected during five field expeditions to Mauritania (2011-2016), allowed the detection of several new crocodile localities (N=26), increasing by 27% the current number of all known locations. Several threat factors affecting crocodile populations and associated habitats were identified (N=11). Droughts and temperature extremes (100% localities affected) and water extraction for domestic use and nomadic grazing (94%) were the most frequently detected. Isolated crocodile populations are apparently vulnerable, especially in the northernmost areas of Mauritania (Tagant mountain), and future local conservation strategies are needed to assure the persistence of its fragile populations. Secondly, an evaluation of the role of climatic oscillations on the spatial and temporal landscape connectivity, genetic patterns and dispersal dynamics of *C. suchus* populations is performed. Genetic diversity, population structure and gene flow of crocodiles are measured, and historical (1980s) and contemporary (2010s) scenarios of landscape connectivity are evaluated, in order to verify if genetic patterns of crocodile populations are correlated with climate-driven patterns of connectivity. Crocodiles display higher levels of genetic isolation in the north of Mauritania, in comparison to the southern populations, indicating effects of isolation by distance. The signs of population connectivity exhibited by juvenile crocodiles are probably related with contemporary dispersal dynamics.

This thesis successfully demonstrates the importance of landscape connectivity for desert organisms and how assessments of biodiversity patterns in desert environments can be improved using RS tools. Interdisciplinary approaches, such as the example presented in this thesis, in which landscape connectivity methods/RS techniques/genetic analyses are combined for assessing local population connectivity of West African crocodiles, are strongly recommended for supporting solid conservation frameworks, principally in overlooked and biodiversity rich ecosystems like deserts environments.

KEYWORDS: Biodiversity distribution; Biodiversity conservation; Biodiversity indicators; Climatic oscillations; Desert environments; Drylands; Hydrographic corridors; Land cover; Landscape connectivity; Mauritania; Mountains; Relict populations; Remote Sensing; Sahara; Sahel; Structural connectivity; Water habitats; West African crocodile; West Sahara-Sahel.

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LIST OF ABBREVIATIONS

ALOS	Advanced Land Observing Satellite
ANN	Artificial Neural Networks
AR	Allelic Richness
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ASTER GDEM	ASTER Global Digital Elevation Map
ATCOR	Atmospheric Correction
AWEI	Automated Water Extraction Index
AWEIsh	Automated Water Extraction Index shadow
BS	Body size
CBD	Convention on Biological Diversity
CC	Correct Classification
CCI	Climate Change Initiative
CF	Circuit Flow
CIBIO	Research Centre in Biodiversity and Genetic Resources
CMTC	Conditional Minimum Transit Cost
CMTC_wb	Conditional Minimum Transit Cost without bottlenecks
COMPS	Compact sand
COMPSO	Compact soil
CROP	Croplands
CRU	Climate Research Unit
CWDS	Cost Weighted Distance Surface
DM	Diffusion Models
EBV	Essential Biodiversity Variables
ECTO	Ectothermic
EGV	Ecogeographical variables
ENDO	Endothermic
ENVISAT	Environmental Satellite
EOO	Extent of Occurrence
ESA	European Space Agency
Fapar	Fraction of Absorbed Photosynthetically Active Radiation
FEC	Fecundity
FR	Full Resolution

FROM-GLC	Finer Resolution Observation and Monitoring-Global Land Cover
GBIF	Global Biodiversity Information Facility
GBM	Generalized Boosted Models
GC	Grains of Connectivity
GEO BON	Group on Earth Observations Biodiversity Observation Network
GIS	Geographic Information Systems
GLC	Global Land Cover
GLM	Generalized Linear Models
GLOVIS	Global Visualization Viewer
G-OM	Graph-only methods
GPS	Global Positioning System
GRAS	Grasslands
GRFL	Gravel floodplains
GSFL	Gravel + Sand floodplains
HCA	Hierarchical Cluster Analysis
He	Expected heterozygosity
HLCM	Hybrid Least-Cost Methods
Ho	Observed heterozygosity
IBM	Individual-based Models
IGN	French Institut Géographique National
ITCZ	Intertropical Convergence Zone
IUCN	International Union for Conservation of Nature
JAXA	Japan Aerospace Exploration Agency
LC	Land Cover
LCC	Least-Cost Corridors
LCP	Least-Cost Paths
LCT	Least-Cost Transects
LiDAR	Light Detection Ranging
MAXENT	Maximum Entropy
MDS	Multidimensional Scaling analysis
MERIS	Medium Resolution Imaging Spectrometer
MIR	Middle infrared
MODIS	Moderate Resolution Imaging Spectroradiometer
MR	Multiple Regression
NA	Non-applicable
Na	Mean number of alleles per locus

NDVI	Normalised Difference Vegetation Index
NDWI	Normalised Difference Water Index
NF	Network Flow
NIR	Near infrared
Np	Number of private alleles
NPP	Net Primary Production
ODUN	Orange dunes
PA	Pseudo-absences
PO	Possible
PR	Present
RaDAR	Radio Detection and Raging
RAIL	Railroads
RGB	Red, Green, Blue
RKM	Resistant Kernel Modelling
ROAD	Roads
ROCK	Bare rock
ROPL	Rocky plateaus
RR	Reduced Resolution
RS	Remote Sensing
RSF	Resource Selection Functions
RSP	Randomized Shortest Path
RUE	Rain Use Efficiency
SAVA	Savannah
SD	Standard Deviation
SDM	Species Distribution Models
SIM	Spatial Interaction Models
SM	Soil Moisture
SMUE	Soil Moisture Use Efficiency
SNP	Single Nucleotide Polymorphism
SOIL_R	Rocky soil
SoNAR	Sound Navigation Raging
SPAN	Salt pans
SRTM	Shuttle Radar Topography Mission
SSI	Simple Structure index
SWIR	Short-wave infrared
TM	Thematic Mapper

TRMM	Tropical Rainfall Measuring Mission
TS	Time Series
TSS	True Skill Statistics
UAV	Unmanned Aerial Vehicles
UNCCD	United Nations Convention to Combat Desertification
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICOR	Universal Corridor Network Simulator
URBA	Urban areas
USGS	United States Geologic Survey
WATB	Water bodies
WDUN	White dunes
WGS	World Geodetic System
YDUN	Yellow dunes

Door, Oualata, Mauritania

Photo:JC Campos

CHAPTER I

General Introduction

The world is like a ride in an amusement park. And the ride goes up and down, and round and round. It has thrills and chills, and it's very brightly coloured, and it's very loud, and it's fun, for a while. Some people have been on the ride for a long time and they begin to question: "Is this real, or is this just a ride?". And other people have remembered, and they come back to us and say: "Hey, don't worry, don't be afraid, because this is just a ride". And we…kill those people."

Bill Hicks, Revelations (1993)

1. LANDSCAPE CONNECTIVITY AND IMPLICATIONS FOR BIOLOGICAL DIVERSITY

Landscape connectivity was firstly defined by Taylor et al. 1993 as the degree to which landscape facilitates or hampers movement of an entity (such as individuals, genes, or seeds) between resource patches. Landscape connectivity represents a major factor driving biological and ecological processes across space and time (Taylor et al. 1993), acquiring special relevance in fragmented landscapes for the persistence of several species (Crooks et al. 2011).

Habitat loss and fragmentation are currently recognized as major threats to global biodiversity (Becker et al. 2007; Lindenmayer and Fischer 2013). Pristine habitats have been progressively converted into smaller and isolated habitat patches, making room to human-dominated landscapes where biotic and abiotic phenomena are disrupted (Fahrig 2003; Fischer and Lindenmayer 2007). Habitat isolation has received increasing attention by biologists over the last decades (Fischer and Lindenmayer 2007; Kindlmann and Burel 2008; Wang and Bradburd 2014; Epps and Keyghobadi 2015; Lechner et al. 2015; Richardson et al. 2016), since isolated populations face greater extinction probabilities due to high proneness to demographic (e.g,. natural fluctuation on yearly breeding success), genetic (e.g,. genetic drift), and environmental (e.g,. natural catastrophes) stochastic effects (Frankham 2005; Baguette et al. 2013). Connected habitats along contiguous environmental gradients allow interactions between selection and inter-patch migration, preventing inbreeding depression and maintaining genetic diversity and demographical/environmental stability (Massot et al. 2008; Vranckx et al. 2012; Cushman et al. 2013). Consequently, preserving landscape connectivity is crucial for assuring the long-term persistence of isolated populations.

1.1. STRUCTURAL AND FUNCTIONAL CONNECTIVITY

Landscape connectivity is not a linear concept (see **Fig. 1.1**), since species can be differently influenced by the landscape traits, depending on the organisms' dispersal ability, the local population densities, and the spatial temporal variation in dispersal

abilities (Manel et al. 2003; Spear et al. 2010). Fundamentally, landscape connectivity can be interpreted according to two major sub-topics: structural connectivity; and functional connectivity. Structural connectivity refers to physical properties among habitat patches, such as patch configuration, matrix of movement resistance, presence of barriers, which allow or impede possible dispersal movements of species (Gilbert-Norton et al. 2010). Functional connectivity is related to species' biological, ecological and behavioural dispersion responses to landscape traits (Baguette et al. 2013). Understanding how these two connectivity components interact and conjugate in the landscape is fundamental for implementing effective defragmentation measures (Gilbert-Norton et al. 2010; Lindenmayer and Fischer 2013).

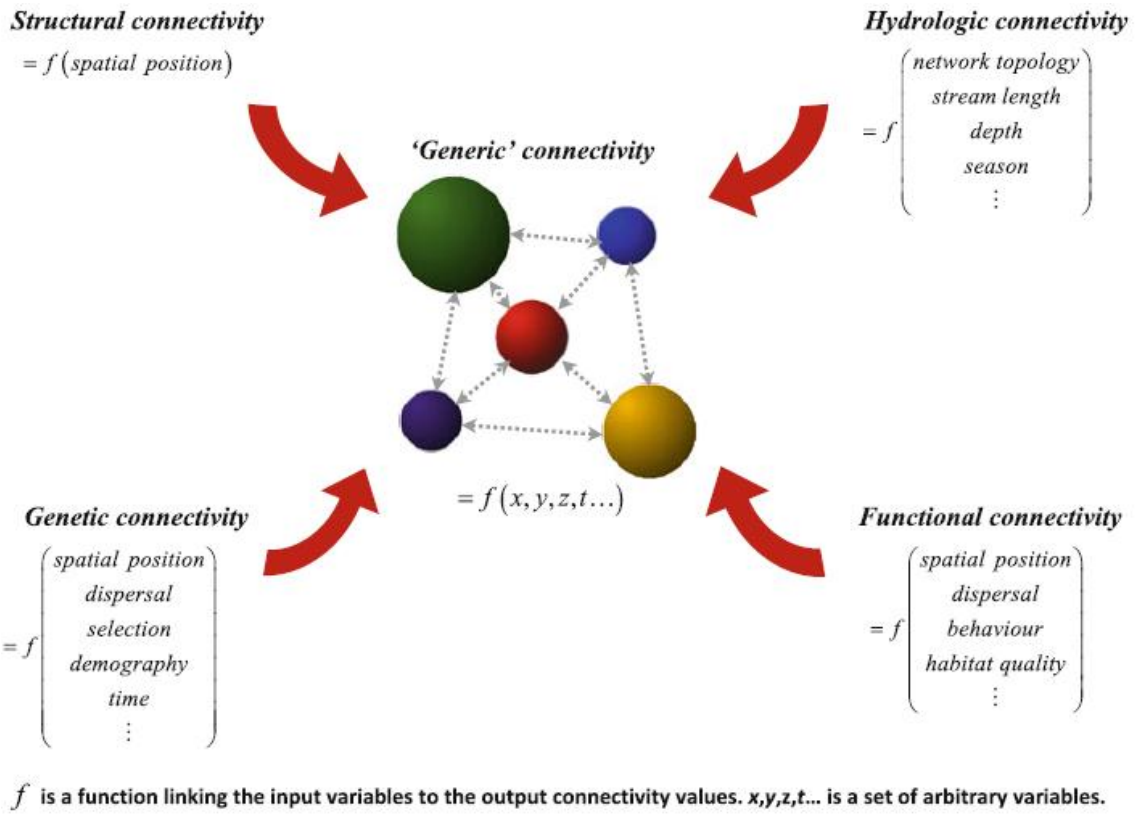

Fig. 1.1 - Different definitions of connectivity. These definitions are not mutually exclusive and may overlap between each other, such as functional and genetic connectivity (extracted from Kool et al. 2013).

Measuring structural and functional connectivity is not a simple task because both components interact in a complex way. In fact, it is well known that the major limitation common to almost all methods focused on structural connectivity is to simplify the complexity of dispersal events by ignoring the full processes that functional connectivity encompasses (Moilanen 2011; Baguette et al. 2013). Such complexities may include dispersal patterns driven by individual biological traits. With enough time and dispersal capabilities, individuals can move to more favourable environments, particularly if they are behaviourally and physiologically flexible (Anderson et al. 2010; Bonte et al. 2012; LaPoint et al. 2013). Nonetheless, functional connectivity is also strongly dependent of landscape structure. Matrix permeability, i.e., sub-optimal or unsuitable habitat surrounding resource patches, and stepping stone patches may determine if particular fragmented populations are functionally connected (Storfer et al. 2010). The presence of dispersal corridors, i.e., landscape features that facilitate movement between ecologically important areas, are also crucial for maintaining the gene flow levels among populations living in fragmented habitats (McRae et al. 2012; Albert et al. 2013). Accordingly, the development and use of practical metrics which objectively measure structural and functional connectivity is fundamental for assessing the degree of landscape fragmentation.

1.2. MEASURING LANDSCAPE CONNECTIVITY

Measuring accurately overall connectivity, i.e., both functional and structural connectivity, is challenging mainly due to two complex factors. First, species ecological and genetic responses to fragmentation may vary in function of species life history traits, such as behaviour plasticity and dispersal ability (Bonte et al. 2012; Wolf and Weissing 2012; Vasudev et al. 2015), and in the amount of generations required for populations to genetically respond (i.e., time-lag effects) to contemporary landscape changes (Landguth et al. 2010; Epps and Keyghobadi 2015). Several non-genetic measures of functional connectivity have been used (see Kindlmann and Burel 2008), which are important for revealing which habitat types may be permeable to movement. Still, these measures remain unable to provide information regarding the successful reproduction of immigrants. From both evolutionary and conservation perspectives, it may be more helpful to use gene flow metrics coupled with spatial statistics (typical landscape genetics framework) to address connectivity issues (Manel and Holderegger

2013; Hall and Beissinger 2014; Anderson et al. 2015; Balkenhol et al. 2016; Dudaniec et al. 2016; Hand et al. 2016; Richardson et al. 2016). Nonetheless, combining different data sources (ecological and genetic data) may provide accurate estimates of functional connectivity, and thus be more advantageous than using genetic approaches alone (Habel et al. 2015).

Second, to adequately represent how structural connectivity may interfere with functional connectivity, suitable spatial/temporal scales and the most suited methods to target species life history traits must be employed (Anderson et al. 2010; Hand et al. 2016). Most methods focusing in structural connectivity have a major limitation related with the oversimplification of species responses to fragmentation (functional connectivity), possibly leading to inaccurate results (Spear et al. 2010; Baguette et al. 2013). This issue is exacerbated on complex landscapes where individuals may react differently to dissimilar types of landscape configuration or different degrees of landscape matrix heterogeneity (habitat surrounding resource patches; Cushman et al. 2012; Driscoll et al. 2013). Accordingly, measuring landscape connectivity requires a carefully planned experimental design which accurately captures species biological and ecological context and habitat heterogeneity across temporal and spatial scales.

1.2.1. GRAPH THEORY AND LANDSCAPE CONNECTIVITY METHODS

Graph theory, developed by Leonhard Euler in 1741 (Euler 1741), was first used in biology to model organisms and their interactions in non-spatial graphs and networks, comprising the basis of almost all methods used for determining landscape connectivity. Graph theory was intensively explored and developed by the mathematician Harary (1969) and his work is still considered as a key reference concerning the study of graphs. Essentially, the Harary's graph is composed by a set of nodes or vertices that can be connected by edges (Harary 1969; **Fig. 1.2**). A path in this graph corresponds to a sequence of nodes connected by edges in a way that a node should not be visited more than once. A graph is considered connected when all the nodes are reachable from other node. In cases where this condition is not verified, the graph is considered as unconnected and, as a result, it is composed by two or more sub-graphs. A connected graph can also be disconnected by the removal of a key node or edge and several sub-graphs can be formed (Urban and Keitt 2001; Gonzales and Gergel 2007). The graph-theoretical concepts previously described can be biologically interpreted and applied on landscape connectivity studies. The landscape is considered as a spatial surface comprising a set of nodes. Nodes can

correspond to habitat patches, populations, individuals, habitat patches, populations, individuals or image pixels, and can be connected by edges representing functional connections (e.g., dispersal corridors). This simple representation of the landscape promoted the development of new methods (Dale and Fortin 2010; Rudnick et al. 2012; Kool et al. 2013; Dyer 2015; Etherington 2016), broadening the methodological spectrum of landscape connectivity. The majority of the landscape connectivity methods developed so far involves the assignment of cost or resistance values to every pixel of an image or raster layer, which in turn represent the landscape. This methodological step is extremely valuable since it allows the inclusion of structural and functional connectivity aspects on the landscape analysis. For these reasons, its parameterization constitutes one of the most important steps on current landscape connectivity studies.

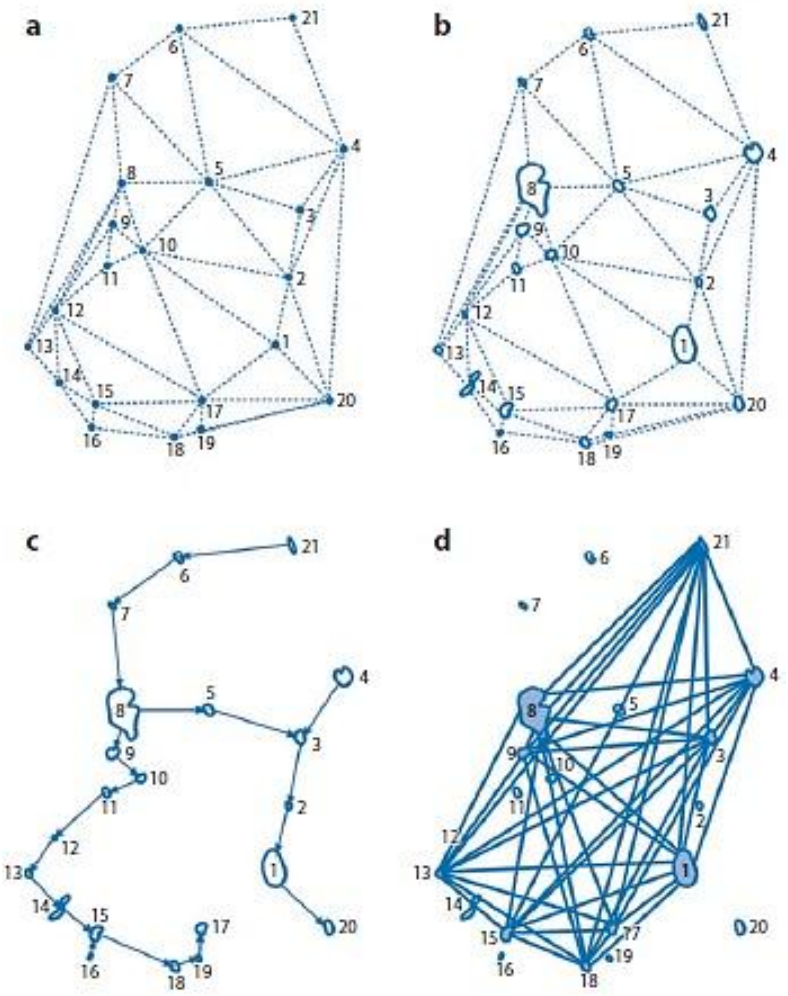

Fig. 1.2 - Types of graphs (extracted from Dale and Fortin 2010). a) non-spatial graph (nodes as numbered dots and edges as dashed lines); b) planar spatial graph (with numbered nodes as potential lakes); c) directed spatial graph, where edges have direction (e.g., water flow); and d) highly connected spatial graph for a sample of lakes in light blue.

1.2.2. PARAMETERIZATION OF COST SURFACES

Parameterization of cost surfaces, i.e., the assignment of resistance values to surface cells, is a crucial step on landscape connectivity studies, linking spatial information (normally through Geographic Information Systems; GIS) and ecological-behavioural aspects of the dispersal ability of an individual (Adriaensen et al. 2003; Spear et al. 2010; Zeller et al. 2012). Resistance values are attributed according to known or estimated relationships among the species ecological preferences and the landscape characteristics. Low resistance values are given to cells displaying suitable ecogeographical conditions, while high values are given to cells exhibiting unsuitable habitats and possible dispersal barriers (e.g., Epps et al. 2007). A cost surface is obtained, identifying different degrees of permeable and impermeable areas for species´ movement. In this thesis, it is exclusively used the concept of cost surface, but other concepts are also applied for the same purpose, such as cost map, friction layer, friction surface, friction map, resistance map, resistance surface, resistance layer, permeability surface and permeability map. The parameterization of cost surfaces can be performed using different approaches (**Table 1.1**). The main constraints of each method can mislead researchers in the selection of an adjusted methodology for parameterizing cost surfaces (Zeller et al. 2012). Still, there are two major classes of methods that can be selected according to the sources of data for parameterization of resistances surfaces: 1) methods based on subjective data; and 2) methods based on empirical data.

Parameterization by subjective data, or expert opinion-based approaches, relies on either the empirical evidence or by taking advantage of previous published papers regarding the biology of a particular organism to assign differential resistance to landscape variables (Cushman et al. 2006; Elliot et al. 2014). Expert opinion is the simplest and less time consuming parameterization method, being especially useful when information about the target species is very hard to obtain. Nonetheless, the subjective process of assigning values to cost surfaces without stipulated decision procedures represents a major inconvenience (Spear et al. 2010; Zeller et al. 2012). Model optimization can be a valuable solution for smoothing biases related with expert opinion methods.

Table 1.1 - Type of data and methods for parameterizing cost surfaces, brief description of each procedure and respective advantages and disadvantages.

Type of data	Method	Procedures	Advantages	Disadvantages
Subjective data	Expert opinion	Assignment of cost values by researchers expert opinion	Easy to perform on well study species and by experienced researchers; cost-effective; allow the test of assumptions based on independent data	Values of cost surfaces depend on expert opinion; no decision procedure associated; different results can be obtained for studies with the same conditions and assumptions
	Model optimization	Attribution of different cost surfaces for the same landscape and consequent statistical assessment for determining the greatest fit with genetic data	Tests several cost surfaces for selecting the one with the greatest fit with genetic data; statistically robust	Values of cost surfaces depends on expert opinion; selection analysis dependent on the type of correlation test
Empirical data	Experimental movements	Tracking of individuals that disperse through artificial landscapes or corridors	Allow the control of several variables related with dispersal movements; no field costs and efforts for collecting data	Costs associated with artificial landscapes; extent of the artificial landscape may not correspond to the real study area extent; artificial landscapes may influence the natural behaviour and dispersal routines

Table 1.1 - Continued.

Type of data	Method	Procedures	Advantages	Disadvantages
Empirical data	Resource selection functions/Habitat suitability maps	Construction of resource selection maps based on empirical data and consequent calculation of resistance by inverting habitat suitability values	Easy to calculate; avoid subjectivity; based on robust statistical models; allow model optimizations for selecting the cost surface with the greatest fit with genetic data	Subjected to constraints of habitat suitability modelling, such as low sample size; important landscape classes for habitat selection might not be relevant for dispersal while others important for dispersal might be ignored; movement and gene flow may operate at different spatial-temporal scales; intensive field efforts and expensive costs for collecting biological data

The use of empirical data is more adequate than expert opinion-based approaches, since they tend to avoid subjective assignments of cost values (Beier et al. 2008; Zeller et al. 2012; Trainor et al. 2013). The presence/absence points, mark-recapture, radio/GPS telemetry, genetic data and experimental movement studies are some examples of empirical data used for parameterizing cost surfaces. Most landscape connectivity studies rely on empirical data coupled with resource selection functions (RSFs) to construct resistance surfaces (Chetkiewicz and Boyce 2009; Shafer et al. 2012; Aarts et al. 2012; Roever et al. 2013; Wang et al. 2013). Several studies have applied this method, obtaining congruent cost surfaces for different study species (Laiola and Tella 2006; Aarts et al. 2012; Epps et al. 2013a,b; Velo-Antón et al. 2013; Razgour et al. 2014). In fact, RSFs avoid the subjectivities associated to cost value assignments and allow a statistically robust parameterization of cost surfaces. Collection of biological data adds more power to parameterization analyses, but several issues must be accounted for. Firstly, at intra-specific level, dispersal and gene flow patterns may vary across sexes or age, and sometimes this aspect is disregarded (Chetkiewicz and Boyce 2009; Epps et al. 2013a). Secondly, when landscape features may be relevant for habitat selection but not for dispersal, inaccurate resistance surfaces may be generated (Zeller et al. 2012). Finally, the intensive efforts and expensive costs needed to collect field data may drive many researchers to choose other parameterization approaches instead.

Researchers trying to parameterize cost surfaces for a certain species, independently of the method used, should acquire as much information as possible regarding its biological traits and perform exploratory tests to acquire consensual estimations of resistance values. A well-defined cost surface is basal for identifying and evaluating key factors that influence landscape connectivity, which ultimately will contribute to well-supported measures for connectivity conservation.

1.3. CONNECTIVITY CONSERVATION

Connectivity conservation is an area essentially focused on identifying and establishing strategies for protecting and/or restoring the continuity of landscape connectivity (Crooks and Sanjayan 2006; McRae et al. 2012). Maintaining landscape connectivity has been considered as probably the most important measure to mitigate the effects of habitat fragmentation (Massot et al. 2008; Rayfield et al. 2011; Vranckx et al. 2012).

For these reasons, the design and management of defragmentation measures represent a crucial step for connectivity conservation and its implementation should be based on solid biological and ecological information (Beier et al. 2008; Gregory and Beier 2014). Several factors may influence connectivity, such as different focal species, distinct area sizes, number of patches and matrix permeability. As such, a preliminary examination of the main questions related to a particular landscape connectivity scenario may allow conservation planners to identify the most effective mitigation measures. Examples of these questions are the importance of which suitable landscape areas are connected, the relevance of the landscape structure for connectivity, what type of patches are important for connectivity and which patches can serve as source or sinks for dispersal (Schick and Lindley 2007; Galpern et al. 2011).

Overall, two major conservation measures are mostly preferred by conservation planners for restoring landscape connectivity: the protection, restoration and/or construction of dispersal corridors; and removal or mitigation of potential landscape barriers to dispersal. Conservation actions focused on dispersal corridors may be crucial for the protection of isolated populations, given the several advantages associated to the restoration of patch linkages (**Table 1.2**). However, other disadvantages may be related to these practices, such as spread of diseases and colonization of invasive species (see **Table 1.2**; Minor and Urban 2008; Haddad et al. 2014). Contrarily, barriers (i.e., landscape structures that impede dispersal movements) may seriously compromise landscape connectivity and lead to the isolation of populations or individuals. Detecting and removing barriers with the most impact to dispersal may maximise the landscape connectivity and decrease the costs associated to landscape restoration, being crucial for effective conservation practices especially when focused on artificial barriers (e.g., fences or road mitigation; Beier et al. 2008; Torrubia et al. 2014; Loro et al. 2015).

Preventing habitat fragmentation and loss would be probably the best solution to maximize conservation efforts (Crooks and Sanjayan 2006), but often, conservation authorities are faced already with post-disturbance scenarios. Restoring habitat quality and compensation measures could also act as effective conservation measures, but budget constraints makes this option unrealistic (Hodgson et al. 2011). Future design and application of defragmentation measures to preserve landscape connectivity will continue to represent probably the best tool available to counteract habitat fragmentation (Beier et al. 2008; Gregory and Beier 2014).

Table 1.2 - Potential advantages and disadvantages of the use of corridors as conservation tools to facilitate connectivity (adapted from Crooks and Sanjayan 2006).

Advantages	**Disadvantages**
(i) Increase immigration rate of a reserve, which could: **(a)** Increase or maintain species diversity **(b)** provide a "rescue effect on small and isolated populations by augmenting population sizes and decreasing extinction probabilities" **(c)** permit recolonization of extinction local populations potentially enhancing persistence of metapopulations **(d)** prevent inbreeding depression and maintain genetic variation within populations	**(i)** Increase immigration rate of a reserve, which could: **(a)** facilitate the spread of infectious diseases **(b)** facilitate the spread of exotic predators and competitors **(c)** facilitate the spread of weedy or pest species **(d)** decrease the level of genetic variation among subpopulations **(e)** cause "outbreeding depression" by disrupting local adaptations and co-adapted gene complexes
(ii) Permit seasonal movements for foraging, breeding, migration, or other behaviours	**(ii)** Facilitate spread of wildfires and other catastrophic abiotic disturbances
(iii) Facilitate dispersal of animals from natal ranges to adult breeding ranges	**(iii)** Create a "mortality sink" by increasing exposure of animals in corridors to humans, native and exotic predators and competitors, pollution, and other deleterious "edge effects"
(iv) Accommodate natural range shifts due to global climate change	**(iv)** Riparian strips, often recommended as corridors, might not enhance dispersal or survival of upland species
(v) Provide predator escape cover for movement between patches	**(v)** High economic cost to purchase, design, construct, restore, maintain, and protect corridors
(vi) Provide wildlife habitat for transient or resident animals within corridors	**(vi)** Trade-off cots and conflicts with other conservation acquisitions, including conventional strategies for enlarging core areas and preserving endangered species habitat
(vii) Provide alternative refuges from large disturbances	**(vii)** Political costs from altering human land-use patterns
(viii) Continuance of ecological processes and ecosystem services such as succession, seed dispersal, and flow of water, nutrients, and energy	
(ix) Provide "greenbelts" to limit urban sprawl, abate pollution, provide recreational opportunities, and enhance scenery and land values	

2. REMOTE SENSING APPLICATIONS FOR RESEARCH IN BIODIVERSITY

Remote Sensing (RS) can be defined as the acquisition of information about an object, area or phenomenon through a device that is not in contact with the subject under investigation (Lillesand et al. 2003; **Fig. 1.3**). This device is usually a sensor installed into a static or moving platform, such as aircrafts or satellites. Remote sensors are typically divided in two groups, the passive and the active sensors. Passive sensors capture reflected or emitted electromagnetic energy (e.g., gamma-ray spectrometers, aerial and video cameras, multispectral and thermal scanners, hyperspectral imagers, microwave radiometers), while active sensors emit their own source of energy to the surface and consequently recapturing the reflected energy (e.g., radio detection raging - RaDAR, light detection ranging - LiDAR; sound navigation ranging - SoNAR) (Richards and Richards 1999; Lillesand et al. 2003). Depending on the mission objective, the sensor-platform system is positioned at specific orbits (in case of satellites) and altitudes, an important factor for determining data resolution. All remote sensors are designed in order to supply images with specific spatial (pixel area measured), spectral (spectral wavelengths that the sensor is sensitive to), radiometric (energy levels measured) and temporal (time of acquisition repeatability for the same area) resolutions (Lillesand et al. 2003; Kerle et al. 2004). Researchers are thus faced with numerous data sources that can be properly selected for answering to quite different questions. For these reasons, the potential of RS tools has been vastly recognized, being used in several research fields, such as Geology, Hydrology, Oceanography and Biological sciences (Rences 1999; Kerle et al. 2004; Jensen 2009).

2.1. BIODIVERSITY DISTRIBUTION AND CONSERVATION

RS has proven to be an effective tool for studies focused in ecology, biodiversity distribution and conservation, given its power in detecting, mapping and predicting key drivers of biodiversity status and trends across the globe (Yang et al. 2013; Pettorelli et al. 2014a; Rose et al. 2015; Willis 2015). The potential of RS tools has been

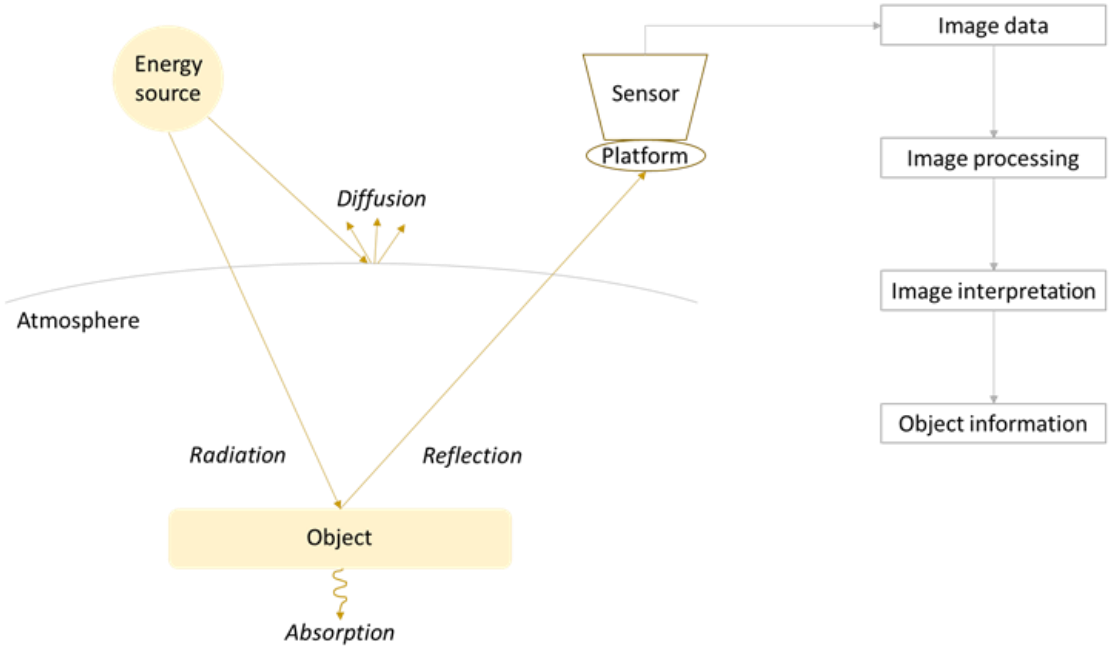

Fig. 1.3 - Principles of Remote Sensing (adapted from Konecny 2014).

increasingly acknowledged by ecologists (Turner et al. 2003; Turner 2014; Rocchini et al. 2015; Szantoi et al. 2016), and the recent efforts to deliver publically available RS data at global scale have boomed their applicability in biodiversity and conservation studies (Wulder et al. 2012; Wulder and Coops 2014; Turner et al. 2015; Yu et al. 2015). However, measuring biodiversity is a complicated task due to its multi-level complexity, leading to a multitude of definitions and metrics that constrain the effectiveness and interpretation of current RS products. Recently, huge efforts have been made by both by RS and ecology communities for targeting the main variables for describing and measuring biodiversity. Under the Convention on Biological Diversity (CBD) framework, the Group on Earth Observations Biodiversity Observation Network (GEO BON) are developing and evaluating the Essential Biodiversity Variables (EBV's), i.e., measurements required for studying, reporting, and managing biodiversity change (Pereira et al. 2013). These variables were set with the objective of assessing biodiversity changes and status over time for establishing a future basis of monitoring programs worldwide (Pereira et al. 2013). Concretely, six classes of EBV's were selected (genetic composition, species populations, species traits, community composition, ecosystem structure and ecosystem functions), constituting targets for obtaining clearer information about biodiversity (Pereira et al. 2013). Accordingly, the RS community have contributed to this cause by selecting RS variables that can

support the monitoring of EBVs. Concretely, ten variables that can be derived through RS were selected until now (Skidmore et al. 2015), namely species populations (species occurrence), species traits (specific leaf area and leaf nitrogen content), four variables of ecosystem structure (ecosystem distribution, ecosystem fragmentation and heterogeneity, land cover and vegetation height), and four variables of ecosystem function (fire occurrence, vegetation phenology, primary productivity and leaf area index, and inundation). These variables can be extremely important as sources of biodiversity indicators and of information that can match the EBV's requirements (Pettorelli et al. 2016a,b; **Table 1.3**). Still, it is required a continuous improvement on the delineation of applicable RS variables that can reflect current biodiversity status and change, and ultimately, that can constitute quality data for supporting effective conservation outlines.

As previously mentioned, species occurrence (and species distribution patterns) is seen as one EBV that can be supported by RS tools. Species distribution patterns are normally determined by a combination of both historical events, such as geographical/climatic barriers and species evolution, and contemporary factors, such as climatic variability, landscape heterogeneity, biotic interactions, species adaptive capacities, water availability and primary productivity (Field et al. 2009; Stein et al. 2014). Amongst these factors, primary productivity is commonly referenced as an important indicator for understanding general patterns of biodiversity loss, a pattern already observed for different *taxa*, such as trees (Kale and Roy 2012), invertebrates (Chase and Leibold 2002), and mammals (Luck 2007). These patterns were confirmed for total species richness at regional (Luck 2007) and wider scales, such as entire biomes (Constanza et al. 2007). The Normalised Difference Vegetation Index (NDVI; a spectral ratio between near infra-red and red bands that highlight the vegetation greenness) and the Fraction of Absorbed Photosynthetically Active Radiation (fAPAR; a biophysical indicator that measures the fraction of the solar radiation absorbed by vegetation during photosynthesis) are two examples of RS variables that can be used to track biodiversity distribution patterns. In fact, the NDVI has been used for inferring species richness of mammals (Youngentob et al. 2015), birds (Kennedy et al. 2014; Nieto et al. 2015), invertebrates (Bailey et al. 2004), and plants (He et al. 2009). These RS variables have also the potential to be implemented in species distribution models (SDM's), another useful application of RS for studying biodiversity distribution patterns. In fact, studies focused on biodiversity distribution have intensively explored RS variables for increasing the performance of SDM's, with land cover and productivity-related variables (e.g., NDVI) exemplifying the most used biotic predictors. Moreover,

Table 1.3 - List of potential RS-based variables that fit, or could fit, the requirements of EBV's (Pereira et al. 2013) at a global level (adapted from Pettorelli et al. 2016a).

EBV class	Examples of RS-based variables currently meeting EBV requirements	Examples of RS-based variables that could meet EBV requirements in the near future
Genetic composition	-	Specific plant genotype diversity
Species populations	-	Species occurrence
Species traits	-	Specific leaf area
Community composition	-	Taxonomic diversity
Ecosystem structure	Fractional cover; forest cover; land cover	Vegetation height; ecosystem distribution
Ecosystem function	fAPAR; leaf area index; vegetation phenology; phytoplankton phenology; soil moisture; fire disturbance; inundation	Above-ground biomass

RS provides an enormous selection of abiotic variables that have been crucial for obtaining improved results from SDM's (Deblauwe et al. 2016). Climatic variables, such as temperature, precipitation and soil moisture datasets [e.g., Climate Research Unit (CRU) dataset (New et al. 2002), WorldClim (Hijmans et al. 2005), Tropical Rainfall Measuring Mission (TRMM) dataset (Huffman et al. 2007), ENVIREM dataset (Title and Bemmels 2017)] and topographic variables [e.g., Shuttle Radar Topography Mission (SRTM) digital elevation data (https://www2.jpl.nasa.gov/srtm/), ASTER Global Digital Elevation Map (ASTER GDEM; https://asterweb.jpl.nasa.gov/gdem.asp)] have been frequently used to improve current predictions of SDM's (Deblauwe et al. 2016; Title and Bemmels 2017).

RS tools can be also applied to directly measure or detect species occurrence at more local scales (He et al. 2015). Hyperspectral data can be used for identifying different plant species (e.g., Féret and Asner 2013), a useful application particularly for the detection of exotic and invasive species (He et al. 2011). Moreover, hyperspectral and multispectral data can be combined with LiDAR measurements in order to identify plant

species with distinct spectral and structural characteristics (Alonzo et al. 2014). Sensors with high spatial resolution have also been used for monitoring several vertebrate wildlife populations (see reviews by He et al. 2015 and LaRue et al. 2017), such as emperor penguins (*Aptenodytes forsteri*; Fretwell et al. 2012), polar bears (*Ursus maritimus*; Stapleton et al. 2014; LaRue et al. 2015), and African megafauna (Yang et al. 2014). The growing use of unmanned aerial vehicles (UAVs) further extends the potential and importance of RS tools for detecting species occurrence at local scales (Turner 2014; Pau and Dee 2016). In fact, UAVs have already been explored for detecting several animal populations (e.g., Koh and Wich 2012; Hodgson et al. 2013). Currently, high resolution RS data remain an expensive solution and its continuous applicability on biodiversity studies will depend on future efforts focused on developing and providing cost-effective data (Turner et al. 2015; LaRue et al. 2017). These future progresses combined with further developments concerning the selection of informative RS-derived variables will most likely increase its application on a larger spectrum of research areas.

2.2. ASSESSMENT OF LANDSCAPE CONNECTIVITY

Given that landscape connectivity and its influence on the organisms' dispersal success are largely dependent on the ecosystem/habitat structure, a currently recognised EBV, RS data stands out as a remarkable source of information for improving studies conducted in this research area. In fact, the potential of RS tools have been intensively explored for the assessment of landscape connectivity over the last years (Zeller et al. 2012; Muratet et al. 2013; Pettorelli et al. 2014b). Land cover, by providing crucial information about the landscape structure and heterogeneity (Yu et al. 2015; Pettorelli et al. 2016a), represents one of the most used RS variables for parameterizing cost surfaces at multiple spatial scales, greatly improving regional and local studies of landscape connectivity (Milanesi et al. 2017). Furthermore, land cover has been recently acknowledged as one of the most important RS variables (Skidmore et al. 2015) for meeting the EBVs requirements (Pereira et al. 2013). In this regard, detailed land cover characterisations may be even more important for arid regions, whose landscape structure is suffering from insufficient and imprecise characterisations, especially in comparison to other regions across the globe (**Fig. 1.4**). Additionally, arid regions are subjected to intensive human activities focused on the

continuous exploitation of scarce natural resources, which ultimately leads to increased poverty, insecurity and social tensions and conflicts (Abdalla 2009; Brashares et al. 2014). The establishment of alternative development scenarios involving the protection of important habitats for biodiversity (e.g., mountain micro-hotspots), but also securing vital ecosystem services for local communities at the same time, stands out as a major priority in arid regions. Predictions of future climate change and increased effects of desertification for the region also represents a worrisome scenario for the persistence of local biodiversity and the welfare of local human populations (Giannini 2015; Cook and Vizy 2015; Lelieveld et al. 2016). Accordingly, providing accurate information about the landscape structure and resource availability might actually constitute the first step for future decision making in the management of important natural resources, as well as monitoring potential effects of climatic variations on current availability of resources.

Climatic factors derived by RS have also contributed for studying connectivity patterns mediated by climate variability (McGuire et al. 2016), providing pivotal information for testing hypotheses of isolation-by-environment (e.g., Wang et al. 2013) and for evaluating connectivity under climate change scenarios (e.g., Lawler et al. 2013; Aguiar et al. 2016). Topographic RS-derived variables have been also been explored in landscape connectivity studies, allowing the representation of altitudinal barriers to dispersal on cost surfaces and the assessment of anisotropic species movements taking into account terrain slope effects (e.g., Rodríguez-Freire and Crecente-Maseda 2008). The construction of hydrological and hydraulic models combining topographic and climatic RS data have also the potential to improve studies focused on hydrological connectivity (e.g., Peterson et al. 2013).

The accuracy of landscape connectivity assessments is strongly related to effects of spatial scale and resolution (Keller et al. 2013). In fact, major corridors or barriers to dispersal may be overlooked if the landscape is represented with an inappropriate spatial resolution. In this regard, the development of emergent sophisticated tools allowing the acquisition of high resolution RS data, such as LiDAR and UAVs, can greatly contribute to the improvement of landscape connectivity studies performed at more local scales (e.g., Milanesi et al. 2017). An accurate scrutiny of local landscape connectivity can be even more important in regions where dispersal paths are naturally scarce, narrow and difficult to detect, such as in desert environments, in which the usage of RS data may constitute an optimal solution.

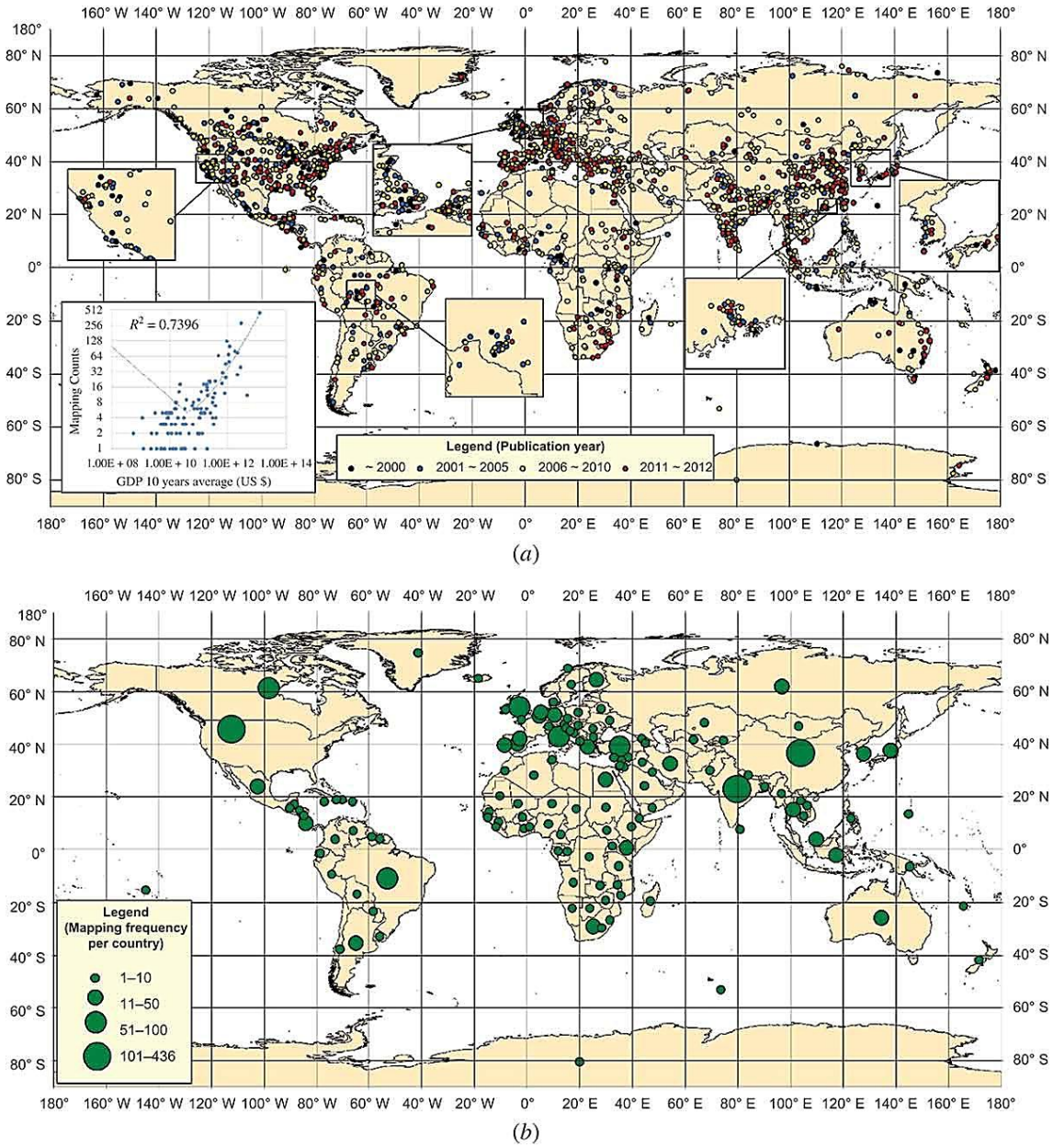

Fig. 1.4 - Land-cover-mapping research around the world (information gathered from 6771 peer-reviewed papers; image extracted from Yu et al. 2014). a) Central location of study areas. The plot shows the correlation between the number of publications and the 10-year average of Gross Domestic Product (GDP) for 2000-2010 (information obtained from the World Bank Group; http://www.worldbank.org/); b) mapping frequency by country.

3. LANDSCAPE CONNECTIVITY AND REMOTE SENSING IN DESERT ENVIRONMENTS

Desert environments [aridity index (average annual precipitation/potential evapo-transpiration) < 0.05; Ward 2009] are generally characterised by severe climatic conditions and by spatial and temporal unavailability of resources (Durant et al. 2012; Van Dam and Matzke 2016). Desert features are typically small and patchily distributed across extensive areas, highlighting both the importance of landscape connectivity for the survival of desert organisms and the use of powerful tools, such as RS, for an accurate detection of natural resources in these remote regions.

3.1. LANDSCAPE CONNECTIVITY IN DESERT ENVIRONMENTS

The scarcity of resources and habitat suitability of desert environments leads to a natural isolation of resident species (Murphy et al. 2012; Davis et al. 2013), being subjected to irregular availability of water sources, primary production and shelters (Shkedy and Saltz 2000). Additionally, the dispersal success of desert species is also abridged by a restricted number of natural corridors and by the presence of extensive and insurmountable barriers (Murphy et al. 2012; James et al. 2017). These factors accentuate the importance of landscape connectivity for species survival in these extreme and remote environments. Moreover, connectivity amongst suitable desert habitats, which have already been considered as island-like systems (e.g., Van Dam and Matzke 2016), may constitute a major factor shaping biogeographical and evolutionary patterns of species.

Landscape connectivity in deserts is majorly mediated by water streams, representing the main way for desert adapted species to disperse between the erratic and isolated habitats in which they endure (Massop et al. 2015; Murphy et al. 2015; Dowell et al. 2015; Davis et al. 2017; James et al. 2017). By conditioning sporadic migration opportunities, water corridors stand out as a key feature to maintain the genetic diversity and gene flow patterns, avoid inbreeding depression and allow rescue effects on small and isolated desert populations (Phillipsen and Lytle 2013; Murphy et al.

2015). Despite the major role of aquatic corridors on species dispersal, water availability in desert environments is strongly linked with climatic conditions. Climatic variations in precipitation regulates both the water dynamics within deserts and also the water flow incomes supplied by major tributaries from desert neighbouring areas (Coulthard et al 2013; Massop et al. 2015). According to recent climate change predictions, that suggest potential precipitation declines and increased temperatures in deserts (Loarie et al. 2009; Pal and Eltahir 2015), water connectivity in these regions might suffer considerable impacts in the future (e.g., Jaeger et al. 2014; Pilliod et al. 2015). Given the typical unpredictability of precipitation regimes and water availability in deserts, these environments represent remarkable case studies for verifying how interactions between climatic and landscape factors might influence population connectivity.

3.2. Remote Sensing in desert environments

RS techniques are particularly advantageous for studying remote regions such as drylands and desert environments, given its success in characterising landscape features in regions where field investigations are difficult to perform. For these reasons, RS has been applied across several arid and hyper-arid regions across the globe for achieving multiple objectives, such as analysis of primary productivity and monitoring of land degradation and desertification (Brandt et al. 2014; Zhang et al. 2016; del Barrio et al. 2016), detection of features associated with oil exploration (Duncan et al. 2014) and analysis of dune dynamics (Mohamed and Verstraeten 2012). However, the detection and characterisation of water systems represents one of the most valuable applications of RS in desert environments. This task is difficult to accomplish, given the characteristically small size, unbalanced water seasonality, and patchy distributions of desert water features (Haas et al. 2009; Soti et al. 2009). The typical remoteness of desert areas also difficult fieldwork assessments. Accordingly, the use of proficient and cost-effective RS techniques (such as Normalised Difference Water Indexes; NDWI) have been greatly explored for the assessment of desert water systems. Concretely, RS tools have been employed for studying the dynamics of desert large lakes (Chipman and Lillesand 2007), delineating the spatial distribution of natural (Haas et al. 2009) and artificial water bodies (Owen et al. 2015), and detecting differences in water availability (Campos et al. 2012; Perrin et al. 2012). The construction of hydrological

and hydraulic models, using RS-derived topographic and climatic data, have also been explored for representing hydrographic networks across desert areas (e.g., Jaeger et al. 2014), an applicability that can significantly improve landscape connectivity studies in these regions. As previously mentioned, water streams are the main factor mediating landscape connectivity in desert environments. As such, hydrographic networks can be easily implemented in cost surfaces, allowing assessments of potential hydrological connectivity between desert populations. Moreover, recent paleohydrological studies applying RS data for discovering previously unknown paleodrainage networks and for assessing potential paleoriver stream flows in desert areas (Coulthard et al. 2013; Skonieczny et al. 2015), reveal prospective contributions of RS to evaluate historical patterns of landscape connectivity.

4. SETTING THE SCENERY

4.1. GLOBAL DRYLANDS

Drylands (tropical and temperate areas with an aridity index < 0.65; Millennium Ecosystem Assessment 2005) occupy approximately 41% of Earth's land area, comprising dry sub-humid, semi-arid, arid and hyper-arid regions (such as desert environments) across the globe. Drylands also symbolise home to more than 2 billion people and stand as remarkable examples of global ecosystems with high levels of biodiversity (Millennium Ecosystem Assessment 2005). These ecosystems are subjected to land degradation and consequent processes of desertification, especially due to the continuous increase of human activities (e.g., exploration of natural resources) and climatic variations (Paganini et al. 2009; del Barrio et al. 2010). The continuous degradation of dryland ecosystems cause severe impacts on the resident local human populations and biodiversity, which led to growing attention by the scientific community worldwide (e.g., the establishment of the United Nations Convention to Combat Desertification in 1994; http://www2.unccd.int/). Given the enormous biological and economical values of these ecosystems, a careful assessment of biodiversity status and change in drylands are thus essential for prioritisation of biodiversity conservation actions.

4.2. THE SAHARA-SAHEL

The Sahara, the world's largest hot desert, and the adjacent semi-arid Sahel (both covering approximately 11,000,000 km^2), are two major African ecoregions (**Fig. 1.5**; Olson et al. 2001) assembling distinctive characteristics in relation to other arid environments. This region comprises a high topographic, land cover and climatic heterogeneities (see **Fig. 1.6**). Topographical features are considerably contrasted, varying between flat areas (e.g., salt pans) below sea level and rough altitudinal peaks distributed along a system of 'mountain-sky islands' (UNEP 2006). The Sahara-Sahel also exhibits a high land cover heterogeneity, including dunes with different

Fig. 1.5 - Limits of the Sahara-Sahel ecoregions, according to Olson et al. (2001). Country names are written in bold.

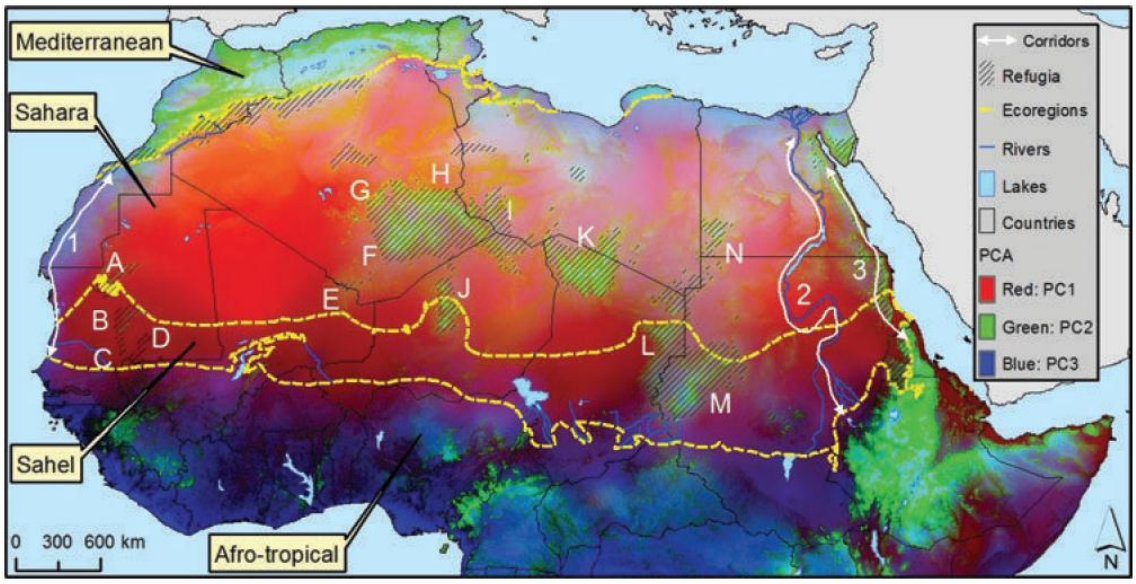

Fig. 1.6 - Environmental variability in North Africa derived by spatial principal components analysis (extracted from Brito et al. 2014). Approximate boundaries between ecoregions (Olson et al. 2001), and hypothesised dispersal corridors (1. Atlantic Sahara; 2. Nile River; 3. Red Sea Sahara) and mountain refugia across the Sahara-Sahel (A, Adrar Atar-Kediet ej Jill; B: Tagant; C: Assaba; D: Afoll´e; E: Adrar des Ifoghas; F: Hoggar; G:Mouydir; H: Tassili n'Ajjer; I: Fezzan; J: Aïr; K: Tibesti-Dohone; L: Ennedi-Borkou; M: Marra; N: Uweinat-Gilf Kebir) (Dumont 1982; Drake et al. 2011). Composite map of spatial principal components analysis, where PC1 (44.0%): annual precipitation, precipitation of wettest month, and temperature annual range; PC2 (33.4%): altitude, annual mean temperature, and minimum temperature of coldest month; and PC3 (9.4%): topography roughness index. Environmental factors from Worldclim database (www.worldclim.org) at 2.5 arc-second resolution.

geomorphological characteristics (e.g., mobile and fixed dunes with diverse soil colourations and vegetation cover), rocky regions (e.g., rock outcrops, rocky plateaus and gravel floodplains), and mountain pools that have been identified as local biodiversity hotspots (Vale et al. 2015). The climatic heterogeneity is denoted by large ranges of spatial variability in temperature and precipitation (average annual temperature ranging from 9.4 to 30.8◦C and more than 981 mm of average annual total precipitation; www.worldclim.org).

The Sahara-Sahel has been also experiencing considerable climatic variations in the past. Paleontological and paleoclimatological studies have confirmed that during the past million years, tropical African climate has oscillated between wetter and drier conditions that led to successive expansions and contractions of the Sahara (Le Hoúerou 1997; Gasse 2000; Claussen 2009). The last wet period registered for North Africa began nearly 15 thousand years ago, a time when the Sahara was covered by widespread grasslands, variable tree cover and large permanent lakes supported by extensive river drainage networks (Prentice et al. 2000; Kröpelin et al. 2008; Tierney et al. 2017; see **Fig. 1.7 and 1.8**). However, a period of aridification started at the Mid-Holocene (around 6,000-4,000 years) due to gradual precipitation declines controlled by the African monsoon, which extinguished most of the savannah-like ecosystems (Schuster et al. 2006; Giannini et al. 2008; Holmes 2008). These historical droughts in the Sahara shifted the Sahara-Sahel boundaries and regional biodiversity patterns, by inducing range contractions and local extinctions of several species adapted to humid habitats (Dumont 1982; Lévêque 1990; Le Hoúerou 1992, 1997).

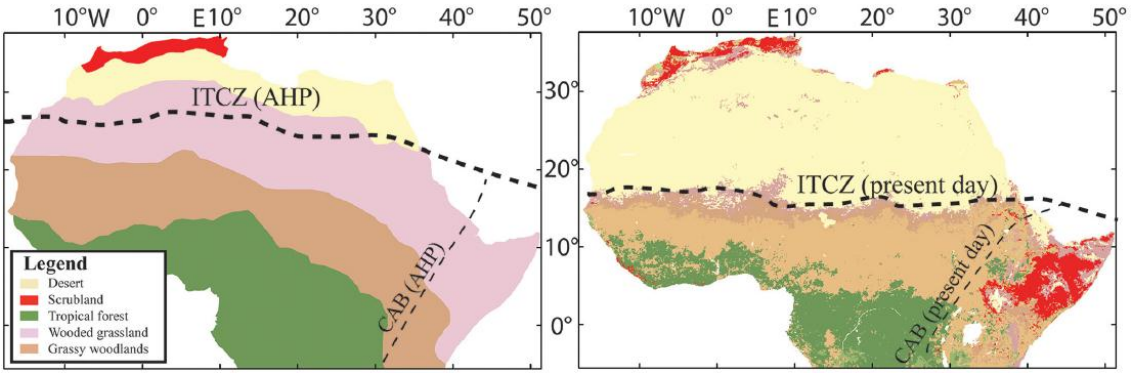

Fig. 1.7 - Left map: Reconstructed African Humid Period (15-5 thousand years ago; extracted from Wright 2017). Biomes were based on Larrasoaña et al. (2013). Average summer position of the Intertropical Convergence Zone (ITCZ) and Congo Air Boundary based on Junginger et al. (2014). Right map: Present-day biomes created from data downloaded from the Atlas of the Biosphere (http://nelson.wisc.edu/) originally digitized from Ramankutty and Foley (1999).

Fig. 1.8 - Late Pleistocene and early Holocene (11 to 8 thousand years before present) palaeohydrology of the Sahara, in which major paleorivers (dark blue), paleolakes (light blue) and paleobasins (green) are presented. Data were extracted from Drake et al. (2008, 2011) and Skonieczny et al. (2015).

The future persistence of Sahara-Sahel biodiversity are under a worrisome scenario, given the predictions of climate change forecasted for the region, estimating possible increases in temperature up to 4ºC and decreases in precipitation of 100 mm for the next decades (Held et al. 2005; Giannini 2015; Cook and Vizy 2015; Lelieveld et al. 2016). The humid conditions of Saharan mountain systems might be critical for the persistency of species, which might use them as potential refugia from severe aridification (see example in Trape 2009). Biological adaptation traits, such as dispersal capabilities, might be also pivotal for resident species to counteract possible effects of habitat/hydrological isolation and extinction risks derived from stochastic events (Pilliod et al. 2015). The unique characteristics of this region are thus a challenge to the adaptive flexibility of resident species, making the Sahara-Sahel a notable example for studying general patterns of biodiversity and the effects of landscape connectivity on the subsistence and dispersal dynamics of species.

4.3. SAHARA-SAHEL BIODIVERSITY AND CONNECTIVITY

The Sahara-Sahel stands out as a remarkably interesting area from a biodiversity point of view. This region encompasses the boundary between the Palearctic and Afro-Tropical biogeographical regions, representing a biogeographic crossroad of increased species richness (Brito et al. 2016). Several species with different biogeographical origins can be encountered across this region, such as Mediterranean (e.g., *Erica arborea*, *Atelerix algirus*, and *Daboia mauritanica*) and Afro-tropical (e.g., *Papio papio* and *Clarias anguillaris*) species. The peripheral populations of non-Saharan species, and the majority of the Saharan endemic species, persist mostly in refugia provided by mountains distributed across the desert (Dumont 1982; Lévêque 1990; **Fig. 1.6**). By providing suitable climatic and habitat conditions, Saharan mountains constitute refugia for several taxa, including fishes (e.g., Trape 2009), birds (e.g., Tellería 2009), herpetiles (e.g., Geniez and Arnold 2006; Vale et al. 2012) and mammals (e.g., Busby et al. 2009; Brito et al. 2010), hosting more than 50% of the Sahara-Sahel vertebrate endemics and for 45% of resident vertebrates with non-Saharan origins (Brito et al. 2014). However, populations residing in these mountains are generally small and exposed to increased isolation, given the harsh conditions of the surrounding areas. Presence of dispersal corridors enhancing population connectivity becomes crucial to counteract the effects of extreme isolation.

The historical landscape connectivity in the Sahara-Sahel was mostly secured by suitable climatic and hydrological corridors. In the past, the humid conditions during the period of the “green Sahara” sustained extensive savannah-like ecosystems, which possibly connected most of the Saharan mountains (Kröpelin et al. 2008). Moreover, these ecosystems were supported by complex and widespread hydrological networks (**Fig. 1.8**), that allowed historical dispersion events of several taxa with different biogeographical affinities across the Sahara (Dumont 1982; Drake et al. 2011). The trans-Saharan dispersal hypothesis is supported by current distribution patterns of several North African species, whose central populations are located at both latitudinal extremes of the Sahara, while the small and isolated relict populations remained in central areas (Drake et al. 2011). Currently, three major trans-Saharan corridors have apparently persisted (**Fig. 1.6**): 1) the permanent Nile River, whose high levels of productivity and water availability provide habitat and dispersal opportunities for more than 40% of Sahara-Sahel endemics and more than 50% of resident species with non-Saharan origin (Brito et al. 2014); 2) the Red Sea coastal region, which holds high

biodiversity levels due to the cooler climatic conditions influenced by the proximity of the sea (Brito et al. 2014); and 3) the Atlantic coastal region of the West Sahara-Sahel, which constitutes a major latitudinal biodiversity corridor sustained by the moderate climate influenced by the Atlantic Ocean (Brito et al. 2014). Consequently, these climatic and hydrological water corridors are of extreme interest given their biodiversity value and their important role on the contemporary dispersal dynamics of Saharan species.

4.4. LOCAL BIODIVERSITY AND CONNECTIVITY: WEST SAHARA-SAHEL EXAMPLE

Beyond the importance of the Atlantic Sahara-Sahel, or the West Sahara-Sahel, as a trans-Saharan corridor, these regions comprise unique features shaping biodiversity and landscape connectivity at more local scales. The West Sahara-Sahel is composed by latitudinal climatic ranges that are ultimately disrupted by major mountain massifs with increased levels of biodiversity. For example, the four major Mauritanian massifs, Adrar Atar, Tagant, Assaba and Afollé, constitute shelter for several endemics and vertebrate species of Afro-tropical origin. Some examples are the endemics Boulenger's agama (*Agama boulengeri*) and the Felou gundi (*Felovia vae*), and the Afro-tropical Rock hyrax (*Procavia capensis*), the Guinea baboon (*Papio papio*) and the West African crocodile (*Crocodylus suchus*). The Adrar Atar is located in the northernmost part of Mauritania, constituting an island-like system given its isolation amongst extensive rocky areas and sand dunes (Monod 1952; Villiers 1953). The remaining three mountains are distributed across southern Mauritania, presenting a milder climate and comprising vegetation with Sudanese origins (Munier 1952; Toupet 1966). Furthermore, the mountains of Mauritania encompass remarkable hydrological features, such as permanent mountain lagoons, locally known as *gueltas*, and seasonal floodplains located at the foothills of mountains, locally known as *tâmoûrts* (Brito et al. 2011a). These water habitats comprise increased levels of biodiversity, being currently considered as micro-hotspots of biodiversity (Vale et al. 2015). Although small and characterised by low water availability, these aquatic habitats may contact during the rainy season (July-October; Cooper et al. 2006).

Connectivity between water habitats might occur both intra and inter-mountains, being mostly upheld by six seasonal hydrographic sub-basins (Campos et al. 2012; **Fig. 1.9**): 1) the endorheic and seemingly isolated Gabbou within the Tagant mountain; 2) the Gorgol el Abiod, that drains water from the southern Tagant and northern Assaba; 3) the Gorgol el Akhdar and 4) Garfa sub-basins, derived from water run-offs of the western Assaba; 5) the Karakoro, that flows between the Assaba and Afollé, being mostly fed by the Afollé run-offs; and 6) the Kolimbiné, that flows to the east of the Afollé. With the exception of the Gabbou, all sub-basins flow to the Senegal River, the main hydrographic feature in the region. The complex hydrological systems of this region provide opportunities for mountain relict populations to disperse, probably inducing metapopulation dynamics within mountains and source-sink events between mountain and southern basin populations (Brito et al. 2011a). However, climate variability in the Sahara-Sahel is typically unstable which lead to unpredictable variations in precipitation, water availability and consequent landscape connectivity. The most striking example of climatic instability in the Sahara-Sahel is demonstrated by the prolonged and unusually dry period between the 1970's and the 1980's decades (Hulme 2001; Giannini 2015; Kaptué et al. 2015). This period has been mentioned as the strongest measured climatic event of rainfall variability at these time and space scales (Foley 2003; Frappard et al. 2009; Dong and Sutton 2015).

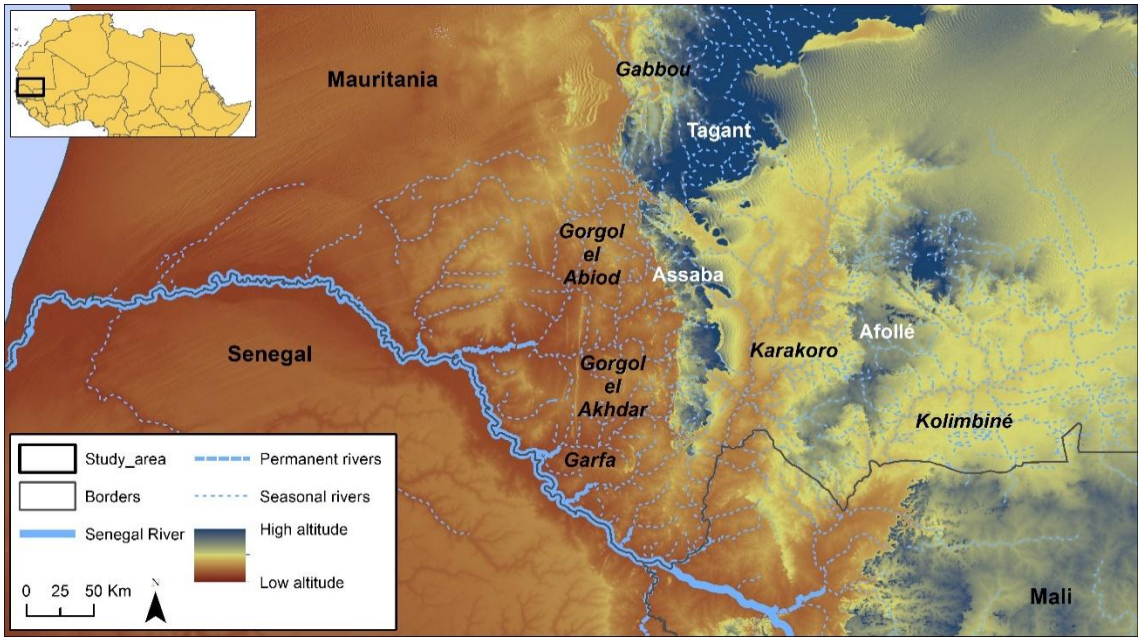

Fig. 1.9 - Mauritanian southern mountains (names in white) and major hydrographical sub-basins (italics). Country names (bold) and boundaries (grey lines) are also presented.

The continuous rainfall decline caused severe environmental impacts, prompting a process of desertification of Sahelian soils due to reductions in primary production and inducing significant drops of stream flows on most of the West African river systems (Kaptué et al. 2015). As an example, the stream of the Senegal River, one of the most important tributaries of West Africa, experienced a decrease of nearly 60% between 1971 and 1979 (ECOWAS 2007). The drought of hydrological courses during this period possibly extinguished several humid habitats and water corridors in the Sahara-Sahel, exposing resident species to increased isolation and extinction risks due to stochastic effects. The mild conditions provided by the Mauritanian mountain habitats and the associated hydrological dynamics are thus crucial for the survival of resident populations, and understanding how climatic-landscape interactions might impact the habitat suitability and landscape connectivity might be critical for protecting the local biodiversity of this region.

4.5. THE WEST AFRICAN CROCODILE

The West African crocodile (*Crocodylus suchus*, Saint-Hilaire 1807) represents a remarkable example of the value of mountain refugia and local landscape connectivity for the survival of relict populations. This species is currently distributed across 22 countries in West Africa (**Fig. 1.10**), ranging from the north and west limits in Mauritania and Senegal, to the south and east limits in the Democratic Republic of the Congo and Uganda, respectively (Hekkala et al., 2011; Shirley et al. 2015; Cunningham et al. 2016). Historically, this emblematic species was widely distributed across the Sahara until the early 20th century, but increased aridity since the Mid-Holocene and intensive human persecutions led to its range contraction and extinction of local populations (Brito et al. 2011a). In the beginning of the 19th century, several exploratory surveys to the Sahara reported the presence of crocodiles in the mountains of Tassili ‘n’ Ajjer in Algeria (see de Smet 1999). In the 1930’s, crocodiles were also reported as present in the southern mountains of Mauritania and in the Ennedi massif of eastern Chad (Hubert 1920; Staudinger 1928; Thesiger 1939; Tubiana 1995). Nevertheless, these reports also acknowledged the precarious status of crocodile populations in the Sahara due mostly to increasing human activities. For these reasons, several crocodile populations became extinct from many localities across the Sahara in the beginning of the 20th century. Some examples are the extinct

populations from the lower Drâa River in Morocco in the 1950's, from the Algerian mountains of Tassili 'n' Ajjer and Hoggar in the 1920's and 1950's, respectively, and from the Chott El Djerid in Tunisia in the 1920's (de Smet 1999). Currently, only a few small and isolated relict populations remain in the Saharan mountain regions of Chad and Mauritania (Brito et al. 2011a)

In Mauritania, the West African crocodile was considered as virtually extinct in the region, despite some reports allegations of crocodile presence in the Tagant mountain and possible presence in the southern mountains of Assaba and Afollé (Quézel, 1978; Behra 1994; de Smet 1999). However, several field expeditions to Mauritania since the beginning of 2000's have confirmed the presence of *C. suchus* populations in the major mountain massifs and associated hydrographic basins (Shine et al. 2001; Nickel 2003; Lluch, et al. 2004; Lluch 2006; Tellería et al. 2008; Brito et al. 2011a,b). These expeditions allowed detecting the presence of crocodiles mostly in the Tagant and Afollé mountains, gathering information for 26 and 4 localities, respectively (Shine et al. 2001; Nickel 2003; Lluch, et al. 2004; Lluch 2006; Tellería et al. 2008). Increased sampling efforts during recent surveys in Mauritania (Brito et al. 2011a,b) allowed detecting the presence of crocodiles in 60 new locations, increasing by 35% the number of previously known localities. These studies assembled information for 78 crocodile localities (Brito et al. 2011a), in which the range of individuals in mountain populations varied from one to more than 20 individuals (although less than five crocodiles were observed for the majority of those localities).

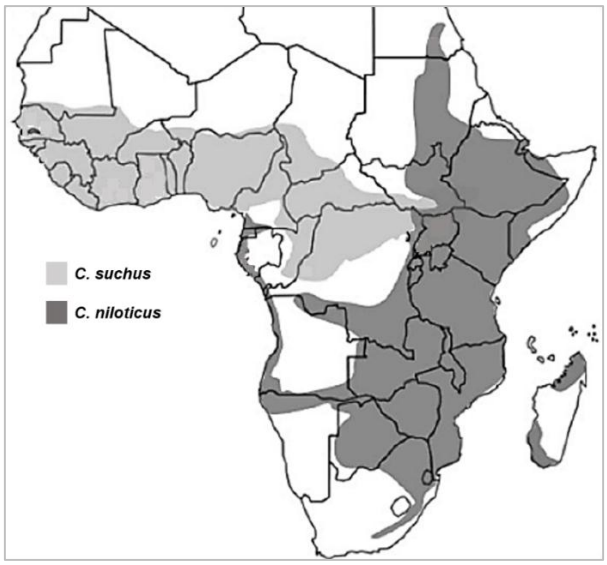

Fig. 1.10 - Distribution range of *Crocodylus suchus* (light grey) and *C. niloticus* (dark grey). The distribution map was obtained and adapted from Shirley et al. (2015).

The crocodile observations during these studies were taken mostly in *gueltas* and *tâmoûrts*, two particular humid habitats associated to the southern mountains of Mauritania. These habitats are thus crucial for the persistence of crocodiles, as well as other vertebrate species in the mountains of Mauritania (e.g., Trape 2009; Padial et al. 2013; Vale et al. 2015). Moreover, the suitable water corridors formed during the rainy season may connect the mountain *gueltas* with *tâmoûrts* and other lowland habitats (Campos et al. 2012), which might allow sporadic dispersal movements and gene flow among crocodile populations. In fact, previous studies using molecular data verified close associations of observed patterns of gene flow and population structure of *C. suchus* to hydrographic sub-basins (Velo-Antón et al. 2014). It was also suggested possible metapopulation dynamics within mountains and a source-sink system between mountain and southern basin populations (Velo-Antón et al. 2014). Accordingly, it is acknowledged that water connectivity plays a substantial role in the persistence of crocodile relict populations on the isolated mountain habitats in Mauritania. Identifying the geographical structure and dynamics of local hydrographic systems could be crucial for interpreting local patterns of landscape (hydrological) connectivity.

Landscape connectivity has experienced an accelerated pace of research during the last years. The increasing number of studies focused on landscape connectivity and the development of numerous methods for measuring structural and functional connectivity, reflect the general growing interest on this research area that still has room for improvements. For instance, crucial improvements to existent methodologies and the development of new ones have been recently conducted (e.g., Bocedi et al. 2014; Kivimäki et al. 2014; Pelletier et al. 2014; Evans and Murphy 2015; Loro et al. 2015; Panzacchi et al. 2016). Despite the several overviews providing general understanding of available methods (Kindlmann and Burel 2008; Dale and Fortin 2010; Sawyer et al. 2011; Rudnick et al. 2012; Kool et al. 2013; Dyer 2015; Etherington 2016), a complementary review summarizing the most recent applied methods and developments, and providing explicit recommendations concerning their applicability in empirical studies is needed for researchers interested in landscape connectivity.

Similarly to landscape connectivity, RS has suffered an escalating research interest and applicability on biodiversity studies. However, despite the recognised contribution of RS data for improving ecological and biodiversity conservation frameworks (Skidmore et al. 2015; Pettorelli et al. 2016a,b), its potential remains largely unexplored in drylands and desert ecosystems (Duncan et al. 2014; Stabach et al. 2017). As an example, the assessments on relationships between functional groups richness and primary productivity are still missing, particularly across global drylands, one of the most representative ecosystems of the world. Also, the land cover heterogeneity of the remote Sahara desert and the arid Sahel ecoregions of Africa are usually undetected in available global land cover maps. Important landscape features across the West Sahara-Sahel (e.g., mountain biodiversity hotspots; Brito et al. 2016) are vaguely classified as extensive and homogeneous bare areas (e.g., the recently accessible Global Land Cover 30 map; Chen et al. 2015), which denotes a major limitation for local biodiversity conservation and management. Exploring freely available RS data might help filling the current gap of knowledge about biodiversity distribution patterns and land cover heterogeneity, particularly in ecosystems acknowledged by many as mostly homogenous and exhibiting low biodiversity in comparison to other regions across the globe (Durant et al. 2012). Moreover, high resolution RS data can greatly improve local assessments of climate oscillations effects over landscape connectivity in the Sahara-Sahel, a pivotal process driving the ecological and evolutionary patterns of desert organisms. The West African crocodile represents a remarkable case study for examining these subjects. Additionally, regardless of the acknowledged importance of crocodiles as a flagship and umbrella species for conservation (Van der Ploeg and van Weerd 2006; Shirley et al. 2009), there is still a lack of knowledge about this species in the Sahara-Sahel. Detailed information about its distribution, population status, and threat factors is still needed for updating its conservation status and to optimise future conservation planning. Assessments of genetic diversity and population connectivity of *C. suchus* are also incomplete. Additionally, using *C. suchus* populations as a model for studying the impacts of climatic oscillations on population connectivity could help understanding this poorly known process across desert environments.

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Fieldwork, Tichit, Mauritania

Photo: JC Campos

CHAPTER II

Objectives and thesis structure

Remember, you can always stoop and pick up nothing.

Charlie Chaplin

1. GENERAL OBJECTIVES

The central objective of this thesis is to verify the importance of landscape connectivity and the application of Remote Sensing (RS) tools for assessing biodiversity patterns in desert environments. This objective is gradually accomplished following four main goals:

1) Assess the current state of structural connectivity methods for application in ecology, evolution and conservation;

2) Verify potential contributions of RS to the assessment of biodiversity distribution patterns in global drylands;

3) Characterise landscape features for the assessment of local biodiversity patterns in the West Sahara-Sahel;

4) Analyse the distribution of West African crocodiles in the West Sahara-Sahel and the effects of droughts on population structure and connectivity.

1.1. DETAILED OBJECTIVES AND THESIS STRUCTURE

The thesis is structured in seven chapters. **Chapter I** consists of a general introduction organised in four main topics. In the first topic, background information about the implications of landscape connectivity for biodiversity is provided, where theoretical concepts about landscape connectivity are explained and where approaches to measure and conserve landscape connectivity are presented. The second topic is focused on the applicability of RS for research in biodiversity, concretely for biodiversity distribution and landscape connectivity studies. The third topic is focused on the importance of landscape connectivity and the application of RS tools in desert environments. In the fourth topic, the study scenery behind this dissertation is contextualised, in which is presented the current knowledge about global drylands, the Sahara-Sahel, the regional landscape connectivity in the Sahara-Sahel, the local landscape connectivity in the West Sahara-Sahel, and the West African crocodile.

Chapter II describes the structure and the general and detailed objectives of this thesis.

Chapter III is focused on the first main objective and is constituted by one manuscript (**Article I**) currently submitted to an international journal indexed in the Science Citation Index (SCI-journal).

Article I is entitled “Methodological advances in landscape connectivity: where are we and where to go?”. This work aims updating previous reviews focused on structural connectivity, by including more structural connectivity methods and reviewing their most recent advances, by providing a synthesis of major advantages/disadvantages underlying each method, and by offering detailed insights concerning research priorities that should be addressed in future studies.

Chapter IV is focused on the second main objective, and is comprised by one manuscript (**Article II**) currently submitted to an international SCI-journal.

Article II is entitled “Remote Sensing indicators and vertebrate biodiversity distribution in global drylands: an assessment with ESA Diversity II products” and is currently submitted in Journal of Arid Environments. This work uses 27 bio-indicators (averages and inter-annual variability of seasonally aggregated proxies for net primary production, rainfall, soil moisture, rain use efficiency, and soil moisture use efficiency) derived from MERIS satellite data and functional species richness of 739 terrestrial vertebrates distributed across five globally distributed drylands, in order to identify the most useful bio-indicators for describing terrestrial non-volant vertebrate distribution patterns in drylands. This work addresses two questions: 1) which RS bio-indicators are most related to total species richness and functional group richness in each dryland?; and 2) are they common across drylands and functional groups?

Chapter V is focused on the third main objective, and is constituted by one manuscript (**Article III**) currently submitted to an international SCI-journal.

Article III is entitled “Revealing unknown land cover heterogeneity in the West Sahara-Sahel and its implications for biodiversity conservation”. This work aims to overcome a major knowledge gap concerning the Sahara-Sahel land cover

heterogeneity, focusing on three detailed objectives: 1) to create a RS-derived land cover map (30x30m resolution) of the West Sahara-Sahel based on an extensive dataset of field control points; 2) to develop an iterative stepwise methodology for land cover class selection and land cover classification; and 3) to improve the current regional land cover mapping

Chapter VI is focused on the fourth main objective, and is constituted by two manuscripts (**Article IV** and **Article V**) currently published and submitted to international SCI-journals, respectively.

Article IV is entitled “Update of distribution, habitats, population size, and threat factors for the West African Crocodile in Mauritania” and is currently published in Amphibia-Reptilia. This work aims to update the knowledge on distribution, occupied habitats, population size, and factors that threaten the West African crocodile (*C. suchus*) and its habitats in Mauritania. Specifically, this study intents to: 1) update the current distribution of *C. suchus* in Mauritania; 2) update the knowledge about the habitats currently occupied by crocodiles; 3) update estimates of crocodile population size at specific localities; and 4) quantify the major threats for crocodile populations and the habitats in which they persist.

Article V is entitled “Unexpected strong distance effects on dispersal and population connectivity of desert crocodiles”. This work aims to evaluate the role of droughts on the spatial and temporal landscape connectivity, genetic patterns and dispersal dynamics of *C. suchus* populations. Concretely, this work aims to: 1) measure the genetic diversity, population structure and gene flow of crocodile individuals; 2) evaluate historical (1980s) and contemporary (2010s) scenarios of landscape connectivity; and 3) verify if genetic patterns of crocodile populations are correlated with spatial and temporal dynamics in connectivity.

Chapter VII consists of a general discussion focused on the general achievements of this thesis, subjects and directions that should be addressed in the future and major conclusions.

Water flow, Guelta El Barda, Mauritania

Photo: JC Brito

CHAPTER III

Review of landscape connectivity methods

If a black cat crosses your path, it signifies that the animal is going somewhere.

Groucho Marx

Article I - Methodological advances in landscape connectivity: where are we and where to go?

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ABSTRACT

Content: Habitat loss and fragmentation negatively affect ecological and biological patterns of populations. Assessing structural connectivity between populations across the landscape is crucial to better understand the effects of fragmentation and to implement effective conservation measures. The number of methodological tools to assess structural connectivity has being growing and previous reviews on the subject have provided the basis for general understanding of particular methods. Still, integrative overviews about their constraints and ecological applications are missing. New approaches have also arisen during the last years, urging the need of updating knowledge about available connectivity methods.

Objectives: We aim updating previous reviews by including more structural connectivity methods and reviewing their most recent advances. We synthesise major advantages/disadvantages underlying each method, and provide insights concerning research priorities that should be addressed in future studies.

Methods: We revised peer-reviewed literature published up to September, 2016.

Results: We summarised the primordial and the most recent methods that have been used to estimate structural connectivity, providing a synthetic guide to help researchers efficiently evaluate the relationship between landscapes and organisms.

Conclusions: Future research should focus on the development of integrative frameworks combining complementary methods to better understand the relationship between landscape structure and species behaviour at structural and functional levels. The increasing computational resources and feasibility in gathering genetic and movement data is allowing the employment of sophisticated methods to evaluate population connectivity. Focusing on these subjects will benefit landscape connectivity and the preservation of overall landscape patterns crucial for population stability and conservation.

Keywords: Circuit theory; Connectivity; Corridors; Cost surface; Dispersal; Graph theory; Individual-based models; Landscape genetics; Least-cost paths; Network theory.

INTRODUCTION

Successful movement of biological material (e.g., genes, pollen, seeds, individuals) between populations is critical for their ecological (mating, foraging, dispersal) and evolutionary (population effective size, genetic diversity and adaptation) stability (Baguette et al. 2013; Richardson et al. 2016). The pronounced acceleration of habitat loss and fragmentation rates since the twentieth century has been largely disrupting this process. Natural habitats have been transformed into smaller and isolated habitat patches embedded in human-dominated landscapes, hindering the movement of organisms and leading to abrupt local population declines and increased extinction risks (Lindenmayer and Fischer 2013). To contribute for an improved understanding of the relationship between heterogeneous landscapes and organisms, Taylor et al. (1993) coined the term "landscape connectivity" – the degree to which landscape facilitates or hampers movements of an entity between resource patches. Over time, a growing interest in landscape connectivity by researchers and conservation practitioners prompted conceptual (e.g., Driscoll et al. 2013) and methodological advances (e.g., Adriaensen et al. 2003; McRae 2006; Panzacchi et al. 2016). Particularly, the need to objectively describe and quantify functional (biological and ecological responses of species to landscape features) and structural connectivity (physical properties among habitat patches, such as patch configuration and matrix of movement resistance) has stimulated researchers to develop increasingly sophisticated analytical tools.

Structural connectivity partly addresses the functional connectivity in the landscape, a current and relevant challenge for landscape connectivity. However, most structural connectivity methods have a major limitation related with the oversimplification of species responses to fragmentation (Spear et al. 2010; Baguette et al. 2013). This issue is exacerbated on complex landscapes where individuals may react differently to dissimilar types of landscape configuration and composition (LaPoint et al. 2013; Vasudev et al. 2015). Structural connectivity is influenced by the research questions and study species, which demands a carefully planned experimental design and the use of suitable methodologies that properly captures species life history traits and habitat heterogeneity across temporal and spatial scales. The accelerate pace of research in landscape connectivity during the last years prompted the development of numerous methods for assessing structural connectivity, which urged the need of

synthetic overviews for assembling and providing general understanding of the available methods (Kindlmann and Burel 2008; Dale and Fortin 2010; Sawyer et al. 2011; Rudnick et al. 2012; Kool et al. 2013; Dyer 2015; Etherington 2016).

Most available studies reviewing structural connectivity methods are focused on particular connectivity methods (e.g., Dale and Fortin 2010; Sawyer et al. 2011; Dyer 2015; Etherington 2016). Recently, Kool et al. (2013) performed an exhaustive review on structural connectivity methods and included the largest spectrum of connectivity methods ever analysed. The authors also addressed functional and structural connectivity, including the discussion of conceptual issues, the challenges associated with landscape connectivity, and possible management applications. However, the strong developments in landscape connectivity methods over the recent last years yielded crucial improvements to existent methodologies and the development of new ones (e.g., Bocedi et al. 2014; Kivimäki et al. 2014; Pelletier et al. 2014; Evans and Murphy 2015; Loro et al. 2015; Panzacchi et al. 2016). Accordingly, a review complementing the work done by Kool et al. (2013) summarizing methods descriptions and recent developments, and providing explicit recommendations concerning their applicability in empirical studies is timely and valuable for researchers interested in landscape connectivity. Here, our main goal is to provide an updated structural connectivity guide for researchers working in landscape connectivity that could help them choosing the most suited method for their own case studies. In particular, we aim to: 1) provide a brief theoretical background behind structural connectivity methods; 2) deliver a brief synthesis of current strengths and weaknesses of structural connectivity methods; 3) update the previous work of Kool et al. (2013) by reviewing additional structural connectivity methods; 4) review recent advances in connectivity methods; and 5) identify research priorities that should be addressed in future studies.

THEORETICAL BACKGROUND

In this section, we provide a synthetic theoretical background of graph and network theories, the basal foundations of most structural connectivity methods. Graph theory (Euler 1741) was first used in biology to model organisms and their interactions using spatial graphs and networks (Hopkins 1957, and then further explored by the mathematician Harary (1969) who defined a graph as a set of nodes or vertices that can be connected by edges.

On landscape connectivity, the landscape can be envisioned as a spatial surface constituted by a set of nodes (e.g., habitat patches, populations, individuals or simply raster pixels) connected by edges representing landscape connections (e.g., dispersal corridors). This simple representation of the landscape promoted the development of new methods, broadening the methodological spectrum of landscape connectivity (**Fig. 3.1**). The most important by-product from graph theory with applications in landscape connectivity is the network theory (Euler 1741). Landscapes, populations, and corridors are subjected to the same ecological interpretations on graph theory, except in two aspects: (1) network methods require an obligatory assignment of numerical values (e.g., cost values) to nodes and edges of a graph; and (2) network methods perform a "step by step" procedure rather than assessing graph configuration globally. Consequently, neighbouring links are calculated progressively along the graph from a source (i.e., initial position of a particular node) to a target node. In practice, values of conductance or cost/resistance (high or low permeability to movement, respectively) are assigned to every pixel of a raster image representing the study area. Assigning cost values to pixels (or parameterization of resistance surfaces) is a crucial step on network-based methods (Dudaniec et al. 2016). This step can be achieved using different criteria (movement, genetic or expert opinion data), but this issue is beyond the scope of this work (but see Spear et al. 2010; Zeller et al. 2012; Graves et al. 2014).

To avoid misinterpretations, we refer to "Graph-only methods" to a major technical group based solely in graph theory (*Graph-only methods* section). Remaining methods include, to some extent, network theory algorithms in their framework.

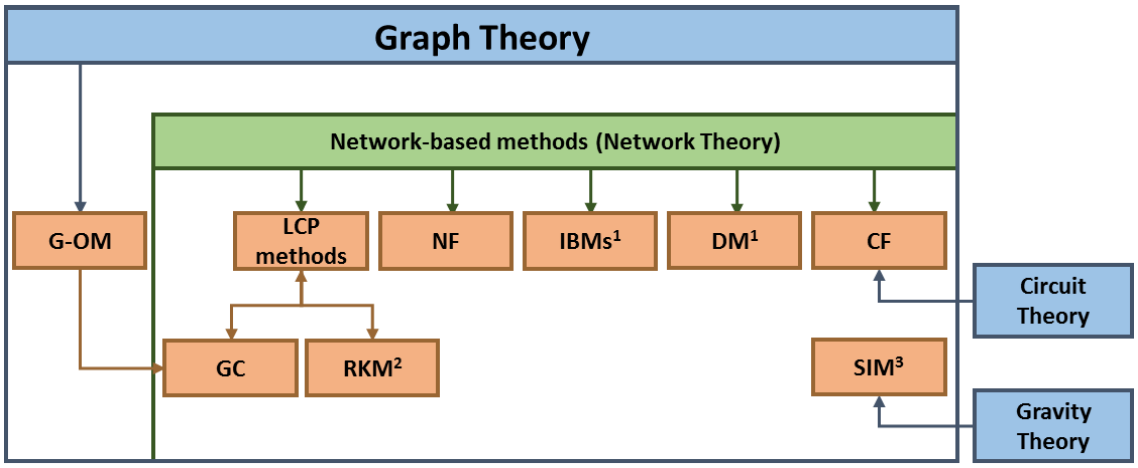

Fig. 3.1 - Main theories associated to landscape connectivity studies (blue boxes), main theory by-products (green box) and derived methods (orange boxes). Acronyms refer to Graph-only methods (G-OM), Least-Cost Path (LCP) methods, Network Flow (NF), Individual-based Models (IBMs), Diffusion models (DM), Current Flow (CF), Grains of Connectivity (GC), Resistant Kernel Models (RKM) and Spatial Interaction Models (SIM). Numbers in superscript indicate: (1) independent methods that use network theory as complementary framework; (2) methods that can be combined with additional methods (e.g., with CF); (3) methods that require an obligatory implementation with additional methods (e.g., with LCP methods or CF).

SYNTHESIS OF CONNECTIVITY METHODS

In this section, we complement the previous work of Kool et al. (2013) by briefly synthesizing current strengths and weaknesses of reviewed structural connectivity methods.

GRAPH-ONLY METHODS

The graph-only methods (G-OM; section “Graph theory” in Kool et al. 2013) were the first to be included in landscape connectivity frameworks (Urban and Keitt 2001; Pascual-Hortal and Saura 2006; Ferrari et al. 2007; Minor and Urban 2008; Albert et al. 2013). G-OM incorporate habitat information by assigning weights to nodes (e.g., habitat suitability metrics) and/or edges (e.g., Euclidean distance between nodes), calculating overall connectivity by examining all possible node connections (Santini et al. 2016; see **Text A.1** in **Appendix A** for examples of distinct G-OM algorithms). G-OM are especially effective when habitat suitability metrics are integrated in nodes and edges (Rayfield et al. 2011; **Table 3.1**).

Table 3.1 - Principal characteristics and potential applications for each of the reviewed method.

Method	Cost surface	Single path	Corridor	Direction dispersal	Potential applications
G-OM					- Assessment of the most important patches and connections for conservation prioritization - Appropriate for metapopulation systems
LCPs					- Identification of the most optimal dispersal corridors at local scales - Useful to assess connectivity on species relying on linear habitat features such as streams or ripicole corridors
LCCs and LCTs					- Identification of the most optimal dispersal corridors at local and regional scales - Identification of multi-pixel wide corridors for analyses of connectivity at community level - Useful to assess connectivity on species relying on linear habitat features such as streams or ripicole corridors
RKM					- Inclusion of ecological data allows a meaningful comparison of landscape connectivity patterns among species - Allows the identification of sub-optimal corridors - Evaluation of landscape connectivity at large scales
GC					- When the adequate spatial scale to the focal species is not known, GC is preferable - Suitable for complex landscapes where multi-scale tests can be done
CF					- Evaluation of landscape connectivity at large scales - Identification of multi-pixel wide corridors for analyses of connectivity at community level - Identification of landscape bottlenecks

Table 3.1 – Continued.

Method	Cost surface	Single path	Corridor	Direction dispersal	Potential applications
NF	■	■		■	- Design of cost-effective corridors by including monetary costs and link capacity - Suitable when there is asymmetric dispersal flow between nodes that significantly affect overall landscape connectivity patterns
SIM	■	■		■	- Suitable when there is asymmetric dispersal flow between nodes that significantly affect overall landscape connectivity patterns - Highly effective evaluation of landscape connectivity patterns at local and large scales through the explicit incorporation of demographic, movement and genetic data
IBMs	■		■	■	- Highly effective evaluation of landscape connectivity patterns at local and large scales through the explicit incorporation of demographic and behavioural data - Suitable for complex connectivity scenarios with high spatial and temporal variability
DF	■		■	■	- Indicated when directional and behavioural dispersal affect the total migration rate - Suitable for complex connectivity scenarios with high spatial and temporal variability

It has been demonstrated that G-OM allow the efficient identification of the most important connections or patches for conservation (e.g., Rayfield et al. 2011), constituting a robust tool for reserve design and conservation prioritization of patches (Minor and Urban 2008; Santini et al. 2016). Moreover, Dyer (2015) reviewed the applicability of graphs in landscape genetics, advocating the usefulness of G-OM to identify the most important source populations to maintain gene flow and associated genetic diversity and structure. Despite their primordial contribution to landscape connectivity, their simplistic representation of reality (i.e., binary classification of the

landscape in patch and matrix) made them largely disregarded compared to other methods (Albert et al. 2013; **Fig. 3.2**). Only on a limited number of situations, where habitat patches (nodes) and corridors (edges) can be realistically represented as discrete units surrounded by an homogeneous matrix (e.g., metapopulation systems and stream corridors), G-OM can be particularly useful (see empirical studies of Urban and Keitt 2001; Minor and Urban 2008; Peterson et al. 2013). For example, Urban and Keitt (2001) applied a minimum spawning tree algorithm to assess an optimized landscape configuration that preserved overall connectivity in populations of Mexican Spotted Owl. Since foraging and nesting sites were surrounded by grass and deserts, the patchy habitat of the Mexican Spotted Owl's suitable habitat was similar to a metapopulation system, making G-OM a convenient approach for this study.

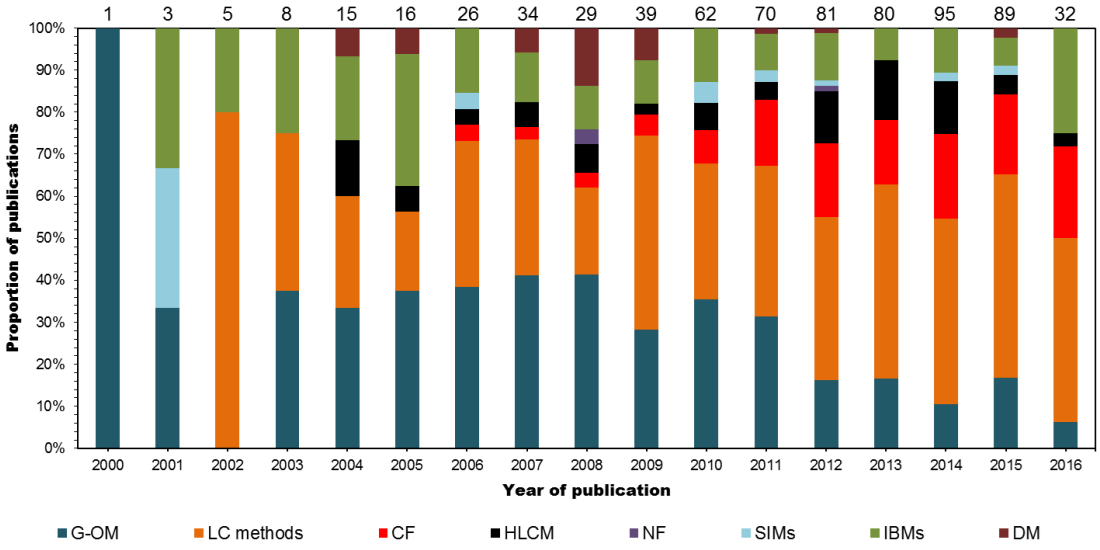

Fig. 3.2 - Publication ratio using different landscape connectivity methods for the period 2000-2016 and total number of publications per year (numbers above bars). Publications were searched using ISI Web of Knowledge (http://pcs.webofknowledge.com/?Func=Exit). Papers were searched yearly and with the phrase ("Landscape connectivity" AND name of each connectivity method). Only research papers were considered. Acronyms stand for Graph-only methods (G-OM), LC (Least-Cost) methods, Current Flow (CF), Hybrid Least-Cost Methods (HLCM), Network Flow (NF), Spatial Interaction Models (SIMs), Individual-based Models (IBMs) and Diffusion Models (DM). Least-Cost methods category includes Least-Cost Paths, Least-Cost Corridors and Least-Cost Transects. Hybrid Least-Cost methods category includes Resistant Kernel Modelling and Grains of Connectivity.

LEAST-COST PATHS

Least-Cost Paths (LCPs) are one of the most used and user-friendly network methods for identifying possible dispersal routes and corridors (e.g., Adriaensen et al. 2003; Rayfield et al. 2010; Sawyer et al. 2011; Etherington 2016; **Fig. 3.2**; see **Text A.2 in Appendix A** for LCP calculations). LCPs greatly benefited from the increasing development of Geographical Information Systems (GIS), enabling an efficient representation of movement costs in complex landscapes with varying habitat quality (Rayfield et al. 2010) and replacing the binary classification of the landscape used in G-OM. This triggered an increasingly employment of LCPs in landscape connectivity studies, including landscape genetics and applied conservation fields (Spear et al. 2010; Baguette et al. 2013; Manel and Holderegger 2013; Muratet et al. 2013; **Table 3.1 and Table A.1 in Appendix A**). However, researchers have been pointing some important limitations, particularly focused on the unrealistic assumption that organisms use the most optimal (lowest cost) path available given its perceptual range of the surrounding landscape (Sawyer et al. 2011). Failure to fully integrate the importance of habitat size, namely the size of source patches or habitat corridor width (i.e., multi-pixel width corridors), represent additional weaknesses (Urban and Keitt 2001; Spear et al. 2010; Sawyer et al. 2011). Yet, LCPs are a very flexible tool and improvements have been made during the last years to circumvent some limitations.

RESISTANT KERNEL MODELLING

The relative straightforward implementation and utility of LCPs make them suitable tools to be combined within distinct analytical frameworks. The Resistant Kernel Modelling (RKM; Compton et al. 2007) results from the combination of theoretical and analytical foundations of LCPs and Resistant Kernel estimators. RKM uses movement information as input (obtained from radio/satellite tracking data or genetic data) to calculate connectivity for all cells/pixels of the study area (Compton et al. 2007; Cushman and Landguth 2012; see **Text A.3 in Appendix A** for RKM theoretical background). This method was successfully used in previous studies modelling connectivity and applied conservation (e.g., Cushman and Landguth 2012; Cushman et al. 2012; Riordan et al. 2016). RKM is computationally efficient and the direct inclusion of movement and life history traits provides the means to perform multispecies comparisons on movement patterns in the same landscape, acting as a good complement of connectivity algorithms (Rudnick et al. 2012). RKM assumes random and directionless dispersal, which may be accurate for large spatial scales. However,

this assumption may be unrealistic at local scales for individuals that perform biased movements based on their knowledge of the environment (e.g., territorial species). Although capable of running with few amounts of data, it is advisable to have high quality field data (e.g., dispersal distance, movement behaviour) of the target species to perform accurate calculations of density kernels (Compton et al. 2007). The lack of robust biological and ecological data is possibly the main cause explaining the low usage of RKM (**Fig. 3.2**).

CURRENT FLOW

Current Flow (CF), or commonly circuit methods, rely partially on graph theory and mechanistically work in similar ways to network methods (i.e., assignment of numerical values to nodes/edges and step-by-step approaches). However, much of their mathematical foundations are borrowed from circuit theory (see **Text A.4 in Appendix A** for Current Flow theoretical background). McRae (2006) proposed combining both theories to address ecological and evolutionary problems by developing tools (namely *CIRCUITSCAPE* software) that incorporated Markov chain algorithms. Contrasting with LCPs and respective methodological extensions, CF enables the processing of all possible pathways between nodes rather than seeking optimal routes (**Fig. 3.3**). This allows capturing dispersal and gene flow patterns at broader and, probably, more realistic scales by assuming that individuals do not travel mandatorily through the most optimized paths or know their surrounding environment (Etherington 2016). Moreover, CF has two other major advantages. First, the use of multi-path processing allows a more efficient identification of optimal multi-pixel wide habitat corridors for movement and narrow linkages of high movement permeability (also called landscape bottlenecks; e.g., road viaducts, valleys), in comparison to G-OM and LCPs derived approaches (Anderson et al. 2014; Rayfield et al. 2015). Second, they allow barrier detection by interpreting voltage changes between voltage maps (in which one voltage map is generated after the removal of an a priori potential barrier), though this task can be accomplished by other methods (see McRae et al. 2012 for barrier detection with Least-Cost Corridors). These benefits, coupled with their relatively straightforward applicability, have made CF a widely used approach in landscape connectivity studies (e.g., Jaffé et al. 2016; **Fig. 3.2**). Like other methodologies, modelling anisotropic flow (e.g., directional gene flow) is not possible under a CF approach (e.g., Murphy et al. 2010). The restriction to Markovian random walks, i.e., random walks in which each step is independent of previous steps, further limits analytically CF to incorporate

behavioural dispersal changes, organisms perceptual range or correlated random walks (McRae 2006; Spear et al. 2010; Wolf and Weissing 2012).

INDIVIDUAL-BASED MODELS

Individual-based models (IBMs) are based on computational simulations of individual dispersal in which behavioural and demographic parameters can be added to simulate dispersal (DeAngelis and Mooij 2005; Grimm and Railsback 2005). Such parameters may be based on individual's perceptual range, inter-individual variability on movement patterns, movement straightness, direction randomness and stochastic effects on demographic traits (Palmer et al. 2011; Bocedi et al. 2014). Accordingly, IBMs have been increasingly used to characterize connectivity patterns under complex scenarios of high spatial and temporal variability (Kool et al. 2013). The complexity underlying these models may constitute a major constraint though, since IBMs require large amounts of precise dispersal data (e.g., radio telemetry data), demographic (e.g., mortality and birth rates) and computational and mathematical expertise to feed the models (but see Grimm and Railsback 2005; DeAngelis and Mooij 2005 for detailed information).

DIFFUSION MODELS

Diffusion models (DM) are a set of dispersal models based on correlated random walks premises which are constructed mainly from mark-recapture data (Ovaskainen 2004; Ovaskainen 2008; Reeve et al. 2008). Currently, DM are able to assess directional biases towards particular habitats at patch boundaries (i.e., in heterogeneous landscapes) through analytical equations (Ovaskainen 2004; Ovaskainen et al. 2008). DM have the advantage of analysing connectivity assuming all possible movement pathways, estimating asymmetric movement rates in different habitat types and between distinct habitat pairs. Relevant biological estimates, such as occupancy probability densities or arrival probabilities at a given patch can be estimated, as well the inclusion of biotic interactions. DMs are computationally efficient by requiring less input parameters, but at expense of lower flexibility and accuracy compared with IBMs. The method also requires large amounts of ecological data to be accurate (Ovaskainen 2008), relying on less intuitive parameters than IBMs. Additionally, DMs framework requires significant mathematical expertise to be implemented. The latter challenge likely precluded its applicability (**Fig. 3.2**), though they can be further explored in

landscape genetics through implementation of genetic data (e.g., asymmetric gene flow rates) to determine diffusion parameters.

UPDATE OF AVAILABLE LANDSCAPE CONNECTIVITY METHODS

In this section, we update the previous work of Kool et al. (2013) by reviewing additional structural connectivity methods.

LCP-DERIVED METHODS

Factorial LCPs represent methodological improvements that surpass LCPs limitation of analysing connectivity between single sources and single sinks (Rudnick et al. 2012). Factorial LCPs are based on pairwise LCP analyses between several sources/sinks that are posteriorly added into a single map showing an LCP density map or cumulative LCP map (Rudnick et al. 2012). The LCP density is more informative than a single LCP analysis, since it indicates the most used paths by several sources and highlights the potential significance of intermediary sources on the dispersal of two distinct sources (e.g., stepping-stone dispersal; see also Cushman et al. 2013). Two additional LCP-derived methods are the Least-Cost Corridors (LCCs; Singleton et al. 2002) and Least-Cost Transects (LCTs; Van Strien et al. 2012). Both are conceptually similar, sharing identical advantages and constraints. LCCs are generated by merging two independent cost weighted distance surfaces (CWDS) estimated independently from its respective source node. They have been used mainly to highlight habitat corridors exhibiting a user-defined cumulative cost threshold between two source nodes (e.g., Singleton et al. 2002; McRae et al. 2012; Nuñez et al. 2013, Lawler et al. 2013). LCTs are buffered LCPs (buffer width chosen a priori), where landscape variables are quantified within a buffer and fitted with a response variable (e.g., genetic distances) to obtain the best statistically supported migratory multi-pixel corridor (Van Strien et al. 2012; Keller et al. 2013; Quéméré et al. 2016). Unlike standard LCPs, both approaches allow the identification of multi-pixel wide corridors, improving efficiency on the identification of optimal corridors at community level to increase overall landscape connectivity (Singleton et al. 2002; Van Strien et al. 2012). Nonetheless, both introduce subjectivity bias related with the choice of cumulative costs thresholds for LCC and buffer size selection for LCT. Unless reliable biological and ecological data (e.g., home range

data, mean dispersal distances) concerning the focal species is available, we recommend researchers to test and compare different thresholds or choose more suited approaches in function of the collected data instead.

Correctly linking landscape structure and biological processes (e.g., gene flow) may be highly dependent of the spatial scale in which analyses are conducted. This issue was brought to attention by Anderson et al. (2010) within a landscape genetics framework and more recently by Galpern et al. (2012), who introduced Grains of Connectivity (GC) in landscape genetics. This approach combines G-OM and LCPs to evaluate landscape connectivity, allowing multi-scale comparisons by varying the grain (pixel) of landscape cover data and assess statistically the most supported spatial scale. The method starts by identifying low resistance agglomerated pixels of a cost surface (grain) that are taken as crucial habitat patches in a landscape. A Voronoi tessellation is then conducted to produce a minimum planar graph on the cost surface, where links correspond to least-cost paths between the node patches (Galpern et al. 2012). A new graph is generated according to a priori established parameters (e.g., spatial scale and cost surfaces), where each node represents an entire Voronoi polygon and the links have the accumulated resistance of the corresponding least-cost path. GC may be valuable to infer how the landscape structure changes according to different spatial scales and to optimise values of cost surfaces according to a chosen spatial scale (Galpern and Manseau 2013). The incorporation of LCPs algorithms in its framework makes GC an excellent tool to address case studies where dispersal occurs at finer scales and when individuals have perceptual range of their surrounding (e.g., less mobile species; Galpern, et al. 2012). However, connectivity may not be properly modelled at regional level overall with LCPs algorithms nor multi-pixel wide corridors can be identified. Similarly to aforementioned methodologies, GC assumes isotropic dispersal, disregarding species biased movements. These disadvantages coupled with a higher difficulty to apply GC compared with other methods, may have discouraged researchers to further explore it.

NETWORK FLOW

Network Flow (NF) was first introduced in ecology by Phillips et al. (2008) to optimize the design of dispersal corridors for a family of endemic plants. A larger emphasis is put (comparatively to G-OM or other network methods) on the efficiency of connections to improve overall connectivity between nodes, without assuming any particular model of organism movement. Analogously to the dynamics of water flowing through pipes

(representing edges), flow can be interpreted as movement rates of biological entities (e.g., genes, individuals, species) between nodes. Each edge has an associated flow capacity that cannot be exceeded. Several algorithms can be employed, but the minimum-cost-maximum-flow, which assesses different maximum flow configurations of edges and nodes minimizing the total cost to preserve them (e.g., monetary cost), was considered very useful in conservation (Carroll et al. 2012).

NF relies on an algorithm that processes multiple pathways to calculate low cost routes, though flow is not dictated by movement probabilities (like in CF) but rather through cost optimization of maximum flow. As discussed above, multi-path processing of organism's movement is more reasonable in most cases, but accurate representation of dispersal at local scales or through linear elements of the landscape (e.g., dispersal alongside a river or stream) is uncertain (Spear et al. 2010; Phillipsen and Lytle 2013). Remarkably, NF allows to model anisotropic flow by assigning distinct weight values to edges representing directions from nodes A to B and B to A. Despite modelling directional flow, changes in flow rate are not accounted (e.g., mortality of dispersers; Bonte et al. 2012) and the method disregards effects of corridor width, which in some cases may hamper its utility for corridor design (Anderson et al. 2014). Nonetheless, NF holds interesting features for the design of cost-effective corridors comparatively to aforementioned network approaches.

SPATIAL INTERACTION MODELS

Gravity models, or Spatial Interaction Models (SIM), combine mathematical concepts of the Isaac Newton's gravitational theory with existing connectivity approaches (G-OM, network or current flow), endowing SIM with great versatility (Murphy et al. 2010; see Watts et al. 2015 for an example of SIM applied with G-OM). After the identification of possible connections through a complementary connectivity method, SIM calculate flow between nodes by assigning attraction and repulsion values to connections. Interestingly, ecological and demographic parameters such as predation, competition, population demographic and genetic data (e.g., census population size, effective population size) can be included to improve their accuracy. Anisotropic flow (e.g., gene flow; Murphy et al. 2010; DiLeo et al. 2014) can also be estimated, making SIM in theory even more compelling, though this premise is not reflected in its usage (**Fig. 3.2**). Their complexity, coupled with computational inefficiency to evaluate several landscapes simultaneously, may have been preventing researchers from using it. Also, parameter estimation relies on parametric assumptions, being sensitive to violations of

independence (e.g., spatial autocorrelation; Fotheringham and O'Kelly 1989; Wagner and Fortin 2005). Given the unique attractive features of gravity models, especially in combination with sophisticated connectivity methods (e.g., circuit methods), research efforts should be focused on improving them to circumvent their limitations.

RECENT ADVANCES IN LANDSCAPE CONNECTIVITY

In this section, we update the previous work of Kool et al. (2013) by reviewing additional structural connectivity methods. In this section, we review relevant methodological developments after Kool et al. (2013).

Despite G-OM being largely deprecated over the years (**Fig. 3.2**), researchers still have been developing these methods. Specifically, Loro et al. (2015) proposed the Conditional Minimum Transit Cost without bottlenecks, (CMTC_wb), in order to improve the original CMTC method developed by Pinto and Keitt (2009). The original CMTC calculates a cumulative cost surface as the combination of the cumulative cost distance between two nodes. The cost surface is then reclassified for corridor identification according to a cost distance threshold defined by the user. However, the original method was limited to subjective threshold selection and to the incapacity of excluding paths with landscape bottlenecks (i.e., narrow linkages in the landscape that sustain connectivity between two areas majorly disconnected; Loro et al. 2015). CMTC_wb surpassed these limitations by selecting the threshold through statistical natural breaks of cost distance values and by varying the classification threshold value until a path connects the pair of nodes without bottlenecks (Loro et al. 2015). The method was applied in a context of road planning assessment to calculate connection probabilities of links, which were posteriorly incorporated on a connectivity index to evaluate graph connectivity. This method seems promising also in heterogeneous landscapes, but as the authors acknowledged, more ecological data (e.g., species dispersal capacity) is required to fully improve both the creation of cost surfaces and its performance, information that may be unavailable for several species.

The incorporation of Current Flow in a user-friendly platform (*CIRCUITSCAPE*), and its features, make it a very appealing tool in most situations, receiving a great support of the scientific community. Thus, similarly to what happened to LCPs, some technical improvements were made. Pelletier et al. (2014) developed the "wall to wall

CIRCUITSCAPE extension" to increment computational efficiency by splitting the study area into "tiles", allowing a more efficient computation of larger area extents. In other cases, methods were target of software development to facilitate their implementation. The framework to conduct SIMs applied to landscape connectivity was recently implemented through a multitude of functions in R package *GeNetIt* (Evans and Murphy 2015). The package allows the construction of spatial graphs, raster manipulation and application of gravity models using landscape data.

IBMs have become a method increasingly explored (Palmer et al. 2011; Panzacchi et al. 2016), but their complexity and implementation in statistical packages required some computational expertise, limiting their dissemination across landscape connectivity studies. Bocedi et al. (2014) introduced *RangeShifter*, a user-friendly platform to circumvent this issue. This platform integrates complex population dynamics scenarios and dispersal behaviour on spatially explicit landscapes. Dispersal is modelled according to three major phases: emigration (departure of individuals from a source), transfer (actual dispersal process) and settlement (occupation of new sites by dispersers). In each phase, several life history (e.g., sexual or asexual reproduction, non- or overlapping generations), demographic (e.g., mortality, individual growth rate) and dispersal (e.g., density-independence, inter-individual variability) traits can be modelled to represent complex scenarios. During transfer phase, the user can employ the Stochastic Movement Simulator (Palmer et al. 2011) or correlated random walks. Furthermore, contributing for the expansion of IBMs in connectivity, Panzacchi et al. (2016) introduced the Randomized Shortest Path (RSP; originally developed by Saerens et al. 2009; and Kivimäki et al. 2014) algorithm. Throughout this review, we discussed the validity of methods assuming optimal individual movements (e.g., LCPs) or random movement (e.g., Current Flow, Network Flow). In several cases, animals perform intermediate movement decisions by trading off movement optimization and random dispersal explorations (Vasudev et al. 2015). After constructing a resistance surface, RSPs are applied according to a parameter that controls the trade-off between optimal and random movements. The output is an intermediate output between least-cost and multi-path algorithms. Thus, RSPs provides a more accurate scenario since an organism will probably disperse by exploring the surrounding environment while minimizing movement costs (Panzacchi et al. 2016). However, the calculation of an optimized randomness parameter according to the study characteristics, requires numerous statistical tests, which might be computing-intensive. Nonetheless, the significant breakthrough that RSPs constitute in characterizing dispersal movement or gene patterns in the landscape, make them a very promising tool for the future.

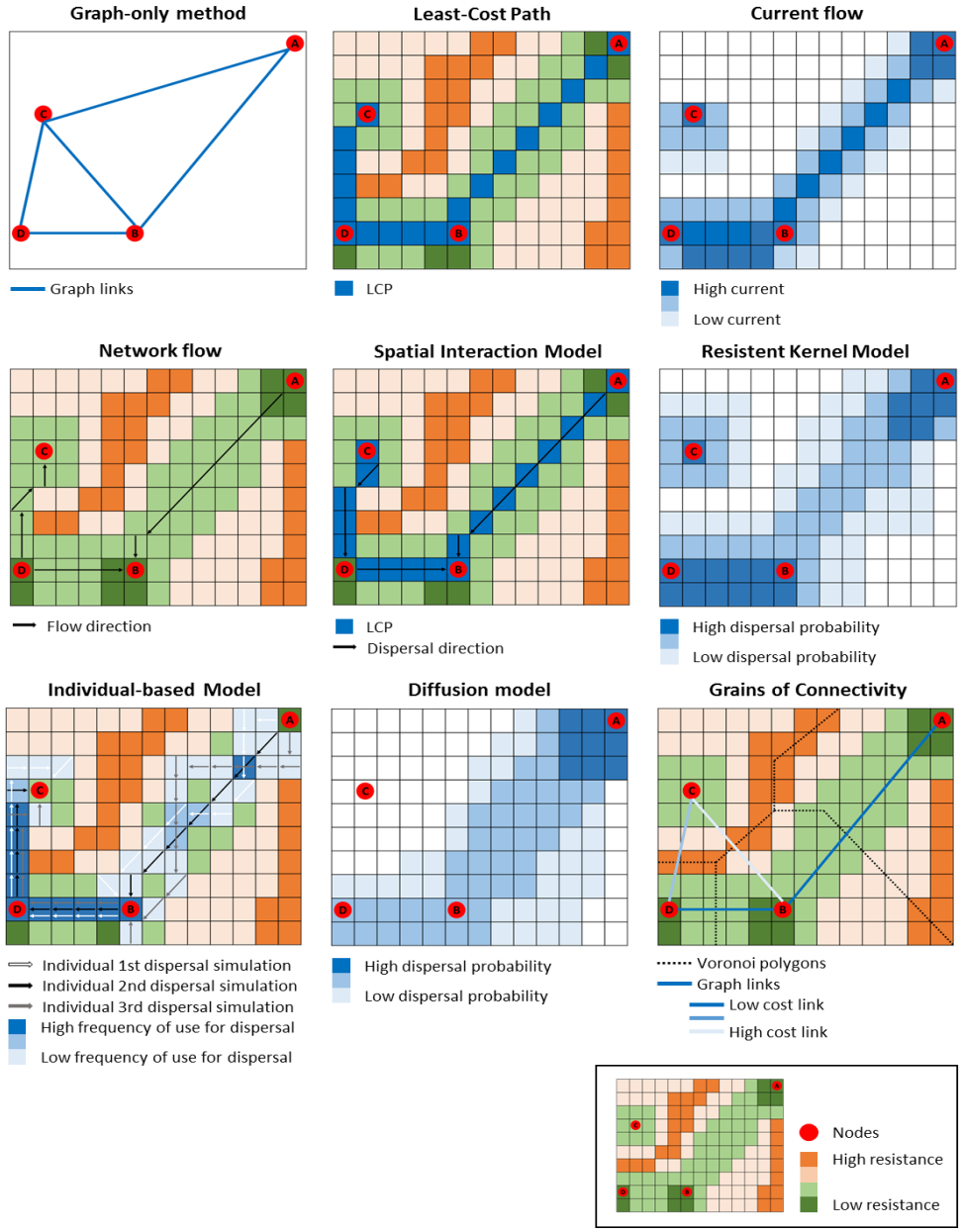

Fig. 3.3 - Example of the application of different landscape connectivity methods in a hypothetical scenario. Nodes represent populations or individuals (red dots), from A to D. The landscape is represented without information (graph method example) or with a cost surface (other examples). The cost surface is constituted by pixels with assigned resistances, varying from low (green pixels) to high (orange pixels). Graph only-methods calculate simple graph links between nodes (blue lines). Least-cost Paths calculate single-pixel paths (dark blue pixels). Current Flow calculate multi-pixel corridors with different current values (can be interpreted as dispersal probability), varying from high current (dark blue pixels) to low current (light blue pixels). Network flow is able to estimate dispersal flow direction across edges (black arrows). Spatial Interaction Models are able to implement dispersal direction (black arrows) into LCPs (dark blue pixels) or other connectivity methods. Resistant Kernel Models calculate probability of dispersal per pixel (blue pixels) through application of kernel density estimators. Individual-based models (IBMs) estimate connectivity based on algorithmic simulations of individual dispersal (white, black and grey arrows representing dispersal of different individuals; exemplified IBM estimates connectivity through directional paths simulations), calculating the frequency of use for dispersal per pixel (blue pixels). Diffusion Models calculate the dispersal probability per pixel (blue pixels) from a source patch, through the application of diffusion equations. Grains of connectivity uses central patch nodes for calculating Voronoi polygons (dashed black lines) and calculates the correspondent LCP's. Graph links are consequently generated, varying from low cost links (dark blue lines) to high cost links (light blue lines).

FUTURE RESEARCH PRIORITIES

In this section, we identify research priorities on the development of structural connectivity methods that should be addressed in future studies.

METHODOLOGICAL DEVELOPMENTS

The application of graph theory and LCPs to assess structural connectivity in the beginning of the 21st century (Urban and Keitt 2001; Adriaensen et al. 2003) was the precursor for the major developments observed in this field. Several methodologies were developed since then, but a discrepancy on their usage is evident (**Fig. 3.2**). Complexity in running specific algorithms (e.g., SIM, IBMs, DM) or lack of empirical studies using a particular method (e.g., SIM, IBMs, DM or GC) led researchers to opt for more practical, yet robust tools (e.g., LCPs, Current Flow). We advocate that more empirical studies using less used methods (e.g., SIM, GC) may enhance its utility for a wider scientific community. For example, a flexible method such as RKM and a multi-scale method like GC may greatly benefit from the combination with distinct methods, such as Current Flow. IBMs are also being subject to an increasing development. For instance, RangeShifter will incorporate the option of simulating genetic data (rather than individuals only; Bocedi et al. 2014) and more efficient algorithms to process RSPs are being developed (Panzacchi et al. 2016). The increase of computational resources and decreasing costs of laboratorial procedures for genetic analyses and GPS telemetry, makes the use of sophisticated methods such as IBMs or SIM more feasible than ever.

The study area extent, life history traits of the focal species, landscape complexity and availability of relevant ecological/demographic data should determine the most suitable method (Dale and Fortin 2010; Vasudev et al. 2015). Capturing all the characteristics of interest in a single method is not straightforward since each method exhibits exclusive features. The on-going developments, particularly in most popular methods (LCPs, Current Flow), broadened their applicability, though their intrinsic constraints demand additional research focused at developing multi-methods frameworks. Multi-method-derived outputs will enable accounting for the unique features of each method, such as the importance of geographic scales (e.g., GC), dispersal abilities (e.g., RKM, SIM), behaviour complexity (e.g., IBMs) or asymmetric flow rates (e.g., Network Flow, SIM, DM). Some studies have already taken advantage of such hybrid frameworks. For

instance, Phillipsen and Lytle (2013) acknowledged this by modelling gene flow using Circuit Flow for land cover variables, while LCPs were employed to model linear elements (streams). Species using mainly linear habitat elements (e.g., streams, riparian corridors) are restricted to these elements (Baguette et al. 2013), and conceptually, LCPs may be more reliable in these cases compared with multi-path algorithms. In another study, Rayfield et al. (2015) combined results from G-OM (e.g., centrality metrics) and Current Flow to identify areas of intra and inter-patch connectivity (through G-OM) and transversal corridors (through Current Flow). Thus, combining output generated from distinct methods to summarize connectivity patterns may be more informative, representing a valuable alternative and powerful tool for conservation planning (see some examples in Anderson et al. 2014). Altogether, hybrid frameworks may provide solid and complementary information, though their implementation is not always straightforward. This can be overcome by the creation of software containing multiple methods that can be merged in a simple way (e.g., Linkage Mapper; http://www.circuitscape.org/linkagemapper). The appearance of some studies combining different approaches to improve structural connectivity analyses represent the "starting point" for integrated frameworks. We believe that investment on sophisticated approaches and integrated frameworks may be particularly useful for researchers to conduct robust studies.

Future studies should also focus in the a priori collection of robust movement (radio/GPS telemetry), demographic (e.g., mark-recapture) and genetic (e.g., microsatellites and SNPs) data to improve functional connectivity estimations. Obtaining field and genetic data is logistically challenging and methods not relying in exhaustive empirical data, collected a priori to increase performance, have been preferred (**Fig. 3.2**). If researchers focus their efforts in acquiring species dispersal information, methods whose performance depends on large data availability (e.g., IBMs) may be selected more often, which could prompt their further exploration, eventual improvements and yield robust connectivity frameworks. In addition to the allowance of precise validations of connectivity outputs, field data helps improving the parameterization of cost surfaces, a crucial step for developing accurate connectivity analyses (Spear et al. 2010; Zeller et al. 2012).

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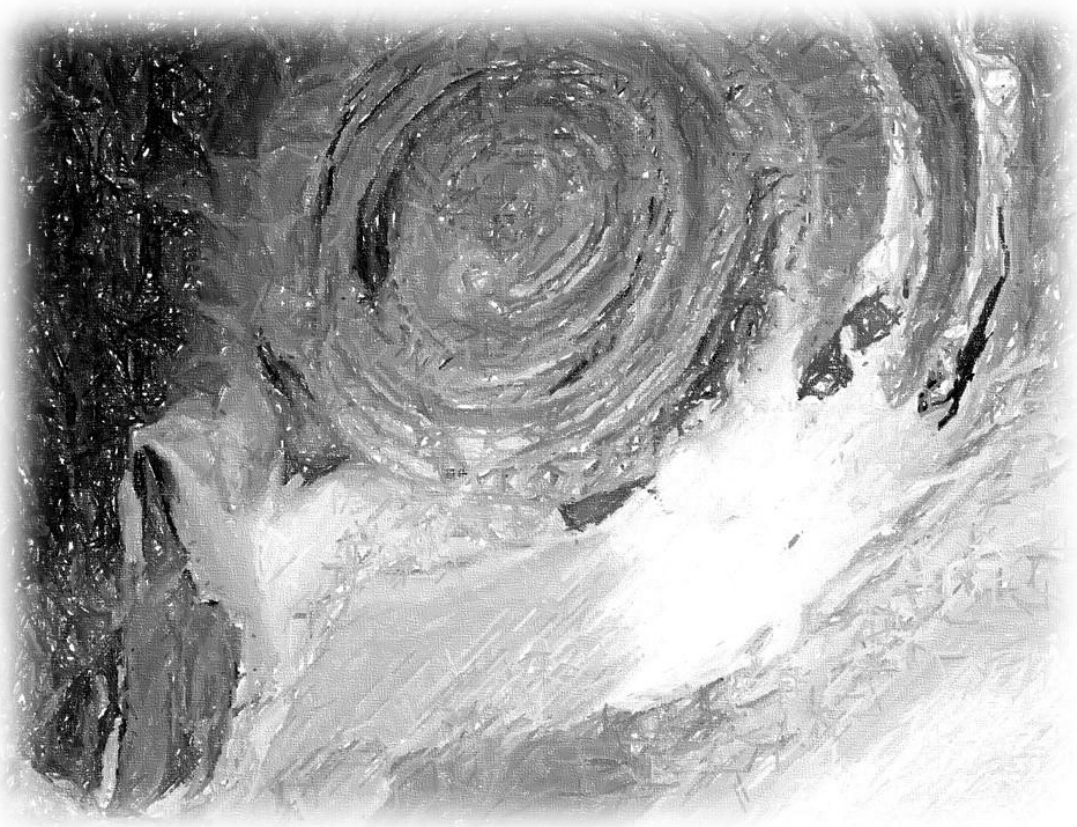

“Eye of the Sahara”, Guelb er Richat, Mauritania

Photo: ALOS satellite (JAXA/ESA)

CHAPTER IV

Remote Sensing and the assessment of biodiversity distribution patterns in global drylands

I don't know anything about Biology, Zoology, Botany, Marine Biology, Evolutionary Biology, Limnology, Climatology, Meteorology, Oceanography, Geology, Geography, Archaeology or Palaeontology…but I think…

Climate change sceptic

Adapted from Stewart Lee, A room with a stew (2013)

Article II - Remote Sensing indicators and vertebrate biodiversity distribution in global drylands: an assessment with ESA Diversity II products

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ABSTRACT

Remotely sensed estimates represent relevant tools for assessing biodiversity distribution, yet their relationships with functional groups across drylands have never been evaluated. We assessed relationship between bio-indicators derived by the ESA Diversity II project and distribution of terrestrial vertebrates in five drylands. Twenty seven bio-indicators were derived from MERIS data, including averages and inter-annual variability of seasonally aggregated proxies for net primary production, rainfall, soil moisture, rain use efficiency, and soil moisture use efficiency. For each dryland, the functional strategy of 739 terrestrial vertebrates was summarized into functional groups and predicted functional species richness was related with bio-indicators. Water availability was better related with functional species richness than net primary production estimates, suggesting water availability as a critical aspect shaping vertebrate distribution in drylands. Body size appeared as an important functional trait influencing vertebrate distribution across drylands, especially in small-sized species associated with water availability. Selected functional traits, quality of species presence data, and ecological modelling approaches affected analyses relating bio-indicators to vertebrate distribution. The 27 bio-indicators showed potential for biodiversity distribution assessments, and may be taken into consideration in future studies with appropriate model adaptations. The followed methodological approach could be applied to other drylands and even other ecosystems.

Keywords: Ecological Niche-based Modelling; Functional groups; MERIS; Primary Productivity; Species Richness; Water availability.

INTRODUCTION

One of the most important goals in biogeography is to understand how species are distributed across the globe and to identify the main factors influencing their spatial patterns (Whittaker et al. 2005). Species distribution patterns are normally determined by a combination of historical events, such as geographical/climatic barriers, and contemporary factors, including climatic gradients, environmental and landscape heterogeneity, biotic interactions, species adaptive capacities, water availability and habitat productivity (Stein et al. 2014). Net Primary Production (NPP) can be used for assessing status and trends in biodiversity distribution, vegetation phenology and primary productivity, and impacts of human-induced land degradation and of climate change on terrestrial biospheres across distinct spatial and temporal resolutions (Pettorelli et al. 2011). Higher species diversity is usually related with higher NPP from local to regional scales and across multiple taxa (e.g., Luck 2007; Nieto et al. 2015). The relationship was observed in total species richness of particular regions (Luck 2007) and in wider biodiversity units, like the value of the ecosystem services of entire biomes (Constanza et al. 2007).

Primary productivity is a key factor affecting biodiversity distribution in drylands (tropical and temperate areas with an aridity index < 0.65; Millennium Ecosystem Assessment 2005). The extreme climatic variability that characterises these regions restrains sustainable water availability and primary productivity (Ward 2009), and exerts pressures on the species' adaptive capabilities, limits species distributions, generates ecological gradients, and increases local endemism rates (Brito et al. 2014). Although relationships between species richness and primary productivity have been observed (e.g., Bailey et al. 2004), variability in such relationships is likely to occur among functional groups (Bailey et al. 2004). These are groups of species showing either similar responses to the environment or similar effects on major ecosystem processes (Gitay and Noble 1997). For instance, in the Sahara-Sahel ecoregions different functional groups exhibit distinct distribution patterns (Vale and Brito 2015), which might be related to different relationships with productivity (Bailey et al. 2004). Nevertheless, assessments on relationships between functional groups richness and primary productivity are missing, particularly across global drylands. Drylands are forefront desertification areas that need urgent assessment of biodiversity relationships with environmental variation (Davies et al. 2012).

Vegetation indices derived by Remote Sensing (RS) have proven to be relevant tools for estimating primary productivity. The Normalised Difference Vegetation Index (NDVI) has been widely used as a productivity proxy in drylands (e.g., Fensholt and Rasmussen 2011) and as a predictor of species richness in multiple taxa (e.g., Bailey et al. 2004; Nieto et al. 2015). Although relationships between NDVI (a spectral ratio between near infra-red and red bands) and species richness are usually positive, studies have also shown that NDVI alone is incapable of predicting relevant patterns of species richness or abundance (Yamaura et al. 2011). Beyond NDVI, different biophysical indices have emerged as proxies of primary productivity. The Fraction of Absorbed Photosynthetically Active Radiation (fAPAR) is a biophysical indicator of above ground productivity, which measures the fraction of the solar radiation absorbed by vegetation during photosynthesis, and has been considered one of the most efficient biophysical indices used in productivity models of terrestrial ecosystems (Gangkofner et al. 2015). Remote sensed estimates of rainfall and the Rain Use Efficiency (RUE), derived from the ratio of the annual primary production and the annual rainfall, have been used as monitoring tools for land degradation (Fensholt and Rasmussen 2011). The Soil Moisture (SM), i.e., the water that remains in the soil or root zone after surface runoff and evapo-transpiration, is considered an Essential Climate Variable by the Global Climate Observing System (see www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables) and constitutes an income for primary productivity (Dorigo et al. 2012). In analogy to RUE, Soil Moisture Use Efficiency (SMUE) can be derived from the SM and NPP (Gangkofner et al. 2015). The European Space Agency (ESA) developed the project Diversity II – Supporting the Convention on Biological Diversity (www.diversity2.info), which aimed to map and evaluate status and trends of vegetation productivity across 22 globally distributed drylands, using the full archive of the Medium Resolution Imaging Spectrometer (MERIS) fAPAR data (2002-2012) from ESA's ENVISAT satellite. A set of 27 biological status indicators were developed to measure various aspects of primary productivity, rainfall and SM, as well as RUE and SMUE at the regional scale (www.diversity2.info/products/drylands). We aim to identify the most useful bio-indicators for describing terrestrial non-volant vertebrate distribution patterns in drylands. Specifically, we address two questions: 1) which bio-indicators are most related to total species richness and functional group richness in each dryland? and 2) are they common across drylands and functional groups? We hypothesized that bio-indicators reflecting water availability might be related to both total and functional group richness and that this might be a common pattern among drylands. We expect to improve the current knowledge about relationships between faunal biodiversity patterns

and primary productivity in drylands and to provide insights concerning the bio-indicators most associated with biodiversity distribution in these regions.

METHODS

STUDY AREA

From the original 22 test sites of the Diversity II project, five dryland sites were used as study areas (**Fig. 4.1**). They were selected based on the representativeness of global drylands, their distribution amongst terrestrial ecoregions (Olson et al., 2001), and their inclusion within the global biodiversity hotspots (www.diversity2.info). The sites were: Australian (≈660,019 km2); Caatinga (≈718,135 km2); South-western Africa (SW-Africa; ≈576,085 km2); Southern Europe (S-Europe; ≈524,698 km2); and West Sudanian Savannah (WS-Savannah; ≈1,641,911 km2) ecoregions. The WS-Savannah dryland was extended to include the southern mountains of Mauritania, comprising portions of the Sahelian Acacia Savannah ecoregion. The extension was performed for including unpublished local distribution data of high resolution (coordinates collected by GPS) available at CIBIO/InBio (authors, unpub. data).

RS DATA AND BIOLOGICAL INDICATORS

The MERIS data from ESA's ENVISAT used for generating the NPP proxies were collected from July 2002 to April 2012. The fAPAR time series data at a bi-weekly time step were derived, based on the algorithm of Gobron (2011) with a ground resolution of 300m at full resolution (FR), which were then supplemented with MERIS reduced resolution (RR) fAPAR data of 1200m in order to fill FR data gaps. The RR data were sub-sampled to match the resolution of the FR data.

A total of 27 "status" indicators were used for the study (detailed in **Table B.1 in Appendix B**). These contain means and variability of the fAPAR based NPP proxies, RUE, SMUE, rainfall and SM data for three major seasonal periods (Gangkofner et al. 2015): a) vegetation year, where averages were derived for the vegetation year, starting at the local start of the growing season and ending approximately one year later at the end of the dry season; b) cyclic fraction, where integrals were generated for the local growing season, starting with the actual start of the green peak of the yearly

vegetation cycle, and ending at the start of the subsequent dry season; and c) dry season greenness, where averages were derived for the dry season, spanning from the end of the growing season to the end of the vegetation year. This resulted in yearly maps of phenologically differentiated productivity means and integrals (2002-2012, covering worldwide eight vegetation years starting in 2003 to 2010), from which averages and coefficients of variations were derived (for details see **Text B.1 and Fig. B.1 in Appendix B**).

In summary, the 27 bio-indicators used are composed by the following groups: 1) Six fAPAR based NPP proxies showing means and variability of vegetation years, cyclic fractions and respectively dry season greenness. 2) Four TRMM rainfall indicators, based on time series of rainfall data from the TRMM - Tropical Rainfall Measuring Mission (http://trmm.gsfc.nasa.gov), containing rainfall means and variability of vegetation years and cyclic fractions; 3) Four SM indicators, based on SM data from the ESA CCI project (www.esa-soilmoisture-cci.org), depicting means and variability of vegetation years and cyclic fractions; 4) Six RUE indicators containing means and variability of vegetation years, cyclic fractions and dry season rain use efficiencies. 5) Six SMUE indicators depicting means and variability of vegetation years, cyclic fractions and dry season SMUE. 6) One indicator showing the mean length of the vegetation season (Lveg), i.e., the time span between the start and the end of the growing season (Gangkofner et al. 2015; **Text B.1 in Appendix B**).

All derived bio-indicators had an original spatial resolution of 300 m, which were then resampled into 1000 m to match species distribution data.

SPECIES LIST AND DISTRIBUTION DATA

The total list of terrestrial non-volant vertebrates occurring in each dryland was collected from GBIF (www.gbif.org). The dataset included 437,893 presence records of 1670 amphibians, reptiles and mammals at 1x1 km resolution. To overcome known issues about accuracy and quality of the geographic, temporal, and taxonomic coverage of GBIF data (Beck et al. 2014), a taxonomic review of selected taxa was carried out based on the IUCN Red List of Threatened Species (www.iucnredlist.org). Reptiles were additionally reviewed based on The Reptile Database (reptile-database.reptarium.cz). Presence records were checked for data duplication (same species records within one pixel) and any taxa with a number of records below 15 were removed from further analyses. The final dataset comprised 739 taxa and 430,239 presence records (**Table B.2 in Appendix B**).

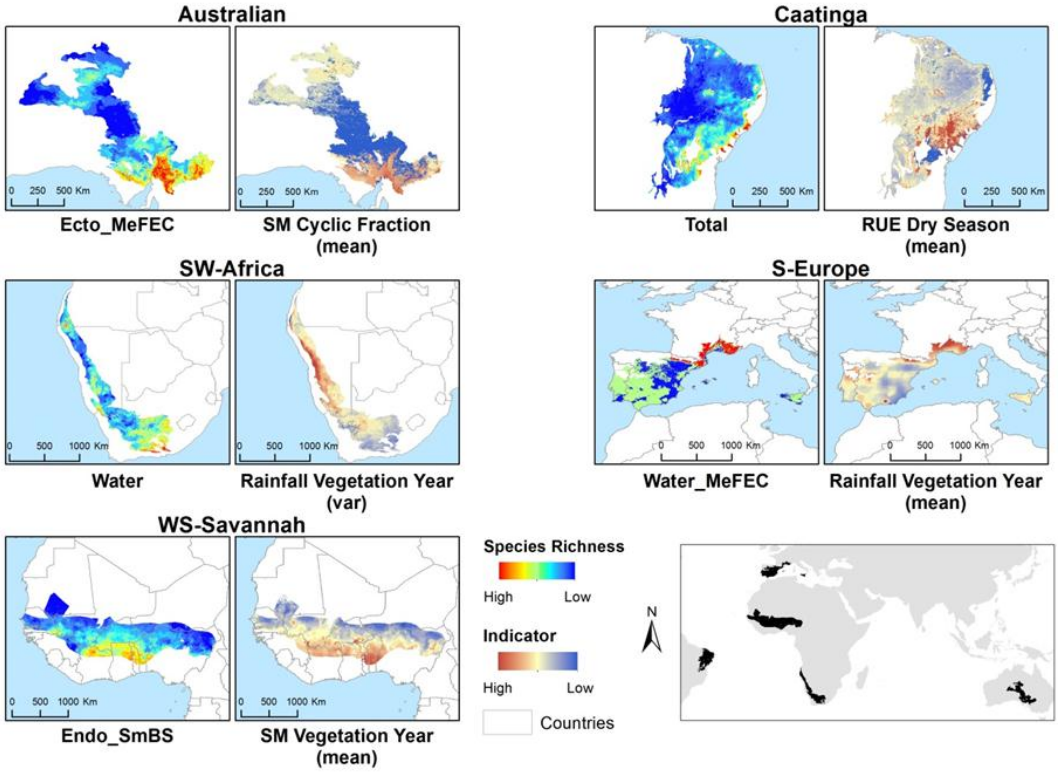

Fig. 4.1 - Geographic distribution of functional groups' species richness and biological indicators. Small inset (bottom right) depicts global distribution of the five dryland study areas (in black). For each dryland species richness is depicted in the left side map, while bio-indicator is depicted in the right side map. Represented functional groups are: Ecto_MeFEC - Ectotherms with fecundity <5 eggs; Water - Water dependent species; Water_MeFEC - Water dependent species with fecundity <100 eggs; Endo_SmBS - Endotherms with body size <30 cm. Represented bio-indicators are: SM Cyclic Fraction (mean) - Soil Moisture Cyclic Fraction (mean); RUE Dry season (mean) – Rain Use Efficiency Dry season (mean); SM vegetation year (mean) – Soil Moisture vegetation year (Mean). SW-Africa: South-western Africa; S-Europe: Southern Europe; and WS-Savannah: West Sudanian Savannah.

FUNCTIONAL STRATEGY AND FUNCTIONAL GROUPS

The functional strategy of each species was described using six biological traits: 1) Thermoregulation, coded as ectothermic or endothermic; 2) Water dependency in some stage of life cycle, coded as yes or no; 3) Reproduction, coded as oviparity, viviparity or ovoviviparity; 4) Fecundity (number of eggs), coded using categories: 1, <5, 5- 10; 10-15; 15-20; 20-30; 30-50; 50-100; and >100 eggs; 5) Body size (cm), coded using categories: <30; 30-100; >100; and 6) IUCN extent of occurrence (millions of km2), coded using categories: <0.1; >0.1; >0.25; >0.5; >0.75; >1; >2.5; >5; >7.5; >10; >25; >50; >75. Trait data was collated from bibliography, public databases and expert knowledge. The functional traits chosen were successfully tested in previous works conducted in arid regions to identify distinction functional groups (e.g., Vale and

Brito 2015). Traits were selected according to two main categories that are thought to be closely related with climatic factors: 1) sensitivity, which includes thermoregulation, water dependency and reproduction; and 2) adaptive capacity, which includes fecundity, body size and extent of occurrence (Foden et al. 2013).

To estimate the level of redundancy among biological traits, a correlation test of each pair of biological traits was performed for each pool of species in each dryland. A distance matrix was created for each biological trait, using Gower distance, as variables are either categorical or nominal (Gower 1971). Then, a Mantel test with the Spearman rank correlation method was performed between every possible pair of distance matrices, using the package "vegan" implemented in R software v. 3.1.1 (R Core Team 2014). Except Thermoregulation and Reproduction ($0.52 > \rho < 0.93$ in all drylands), all biological traits had correlations values below 0.38.

A pairwise differences matrix between species in each dryland was computed using Gower distance. This allowed calculating multivariate distances between species based on the raw biological trait data. Equal weights were given to each biological trait, except for the correlated Thermoregulation and Reproduction, which were treated as attributes of a unique qualitative biological trait, requiring different weights (0.5 for each one). The weight was calculated based on $wi = xi/bi$, where xi is the original weight given to the biological trait i and bi is the number of attributes required to re-code trait i (Laliberté and Legendre 2010). The "k-means" method and the Simple Structure index (SSI) were used to estimate the number of functional groups.

ECOGEOGRAPHICAL VARIABLES

Three sets of environmental factors, or ecogeographical variables (hereafter EGV) were used for building ecological niche-based models (**Table B.3 in Appendix B**). These EGVs were selected for the ecological models according to their meaning to the ecology and distribution of biodiversity in arid regions (e.g., Brito et al. 2011; Vale et al. 2014). The sets include: 1) one topographical grid that was used to derive the variable Slope (Worldclim; www.worldclim.org); 2) six climate grids (annual mean temperature, maximum temperature of warmest month, minimum temperature of coldest month, annual precipitation, precipitation of wettest month, and precipitation of driest month) representing averages, extremes and seasonality in precipitation and temperature levels (1950-2000) from Worldclim; and 3) a land-cover grid from the year 2009 (Globcover 09; http://due.esrin.esa.int/globcover). To convert the categorical land-cover EGV into a continuous variable, one binary grid was created for each land-cover type

and the Euclidean distance of each grid cell to the closest land-cover type was calculated for each individual land-cover grid. Converting categorical (presence/absence of a land-cover type) into continuous variables (distance to a land-cover type) has been widely used in species distribution modelling in drylands (Brito et al. 2011; Vale et al. 2014). Only land-cover classes that covered more than 5% of each continent were considered for these analyses (**Table B.4 in Appendix B**). Overall, most variables were correlated at r<0.75 with some exceptions (**Table B.5 in Appendix B**). Strong correlations can affect model parameterisation, but since the focus was to retrieve the best possible predicted distribution and not to identify the most important variables associated with species distribution, we opted to use all variables in ecological models. Finally, two sets of EGVs were created: 1) a continental set of EGVS at 10x10 km; and 2) a regional set of EGVs at 1x1 km corresponding to each test site. EGVs were resampled from the original (1x1 km) to 10x10 km resolution.

The degree of correlation between EGVs (regional set) and biological indicators was assessed with Pearson's rank order correlation analysis. Analyses were performed in ArcGIS 10.1 using the built-in Band Collection Statistics tool (ESRI 2011). Few correlations were found throughout drylands (**Table B.6 in Appendix B**), with the exception of the West Sudanian Savannah (still less than 5% of all possible relationships), and Southern Europe displayed no correlations.

ECOLOGICAL NICHE-BASED MODELS AND SPECIES RICHNESS PREDICTIONS

Ecological models were constructed at a continental level and then projected to the correspondent dryland sites. This procedure was selected for including the complete species environmental range and, thus, to fully assess the species-environment relationships (Thuiller et al. 2004).

Ecological models were performed on *Biomod2* package (Thuiller et al. 2012), which is a collection of functions running within the R software. It has been acknowledged that different modelling techniques can provide distinct results, depending on how the species-specific tuning parameters are defined and on which kind of presence data are used to build models (e.g., presence-only models vs. presence-absence models). Given the high number of species under analyses, exhibiting distinct distribution patterns across drylands located throughout the globe, and the asymmetries in sample sizes of observations for model building, we opted to test dissimilar types of model techniques that are based in different types of presence data (**Fig. B.2 in Appendix**

B). This approach allows deriving consensus maps, which minimize modelling uncertainties by weighting all the occurrence predictions (for details see Thuiller et al. 2009). After a preliminary analysis, four model types (GLM, generalized linear models; ANN, artificial neural networks; GBM, generalized boosted models; and MAXENT, maximum entropy) were chosen from the initial 10 modelling algorithms available in *Biomod2*, due their high performance with relatively low sample sizes (e.g., Hernandez et al., 2006).

The four different modelling algorithms require distinct observational data: both presence and absence data for GLM, and presence-only data in ANN, GBM, and MAXENT (Phillips et al. 2006; Thuiller et al. 2012). As such, two datasets of pseudo-absences were randomly created for each species in *Biomod2*. A large number of pseudo-absences were created for each dataset of each species (10000) to obtain the most accurate results reported using GLM and MAXENT algorithms (Barbet-Massin et al. 2012).

All models were produced using default *Biomod2* parameters whenever possible (Thuiller et al. 2012). The number of pseudo-absences were chosen to have the same weight as presence data in the calibration process, i.e., prevalence=0.5 (Barbet-Massin et al. 2012). A total of 80% of occurrence data were randomly assigned to model training with the remaining 20% for model testing. Individual models were evaluated using the true skill statistics (TSS), which has been demonstrated as highly effective for assessing model performance (Allouche et al. 2006). Only models with TSS>0.70 were kept for subsequent analyses, except in the Caatinga dryland site where the threshold was decreased to 0.5 due to the low number of models produced with TSS above 0.70.

Individual model replicates were added to generate mean forecasts of probability of species presence in each dryland. To obtain species richness maps, the consensus forecasted probabilities of occurrence were converted to a binary value of predicted presence/absence using an optimized threshold automatically selected by *Biomod2*. The selected threshold maximizes both the sensitivity and specificity of models, i.e., maximizes the correct classification rate of both observed presence and absence data (Liu et al. 2013). Finally, both total species richness and species richness of each functional group for each dryland site were estimated by adding the individual predictions of species presence/absence in each grid cell (Brito et al. 2011).

CONTRASTING BIOLOGICAL INDICATORS AND SPECIES RICHNESS PREDICTIONS

Multiple regression-based models (MR) are strong and robust method to analyse relationships between predictors and dependent variables (Aiken et al. 1991), and have been used to analyse relationships between species richness and environmental variability (e.g., Colwell et al. 2016). MR were applied in this study to identify the model best describing relationships between bio-indicators and the predicted functional group richness and total species richness in each dryland. The MRs were developed using subsets of the supplied 'global' model that were chosen using the function dredge implemented in the *MuMIn* package in R software v. 3.0.2. The dredge function was used to generate a set of models with subsets of the global model. This is a robust approach as models are fitted through repeated evaluation of modified call extracted from the global model. The MRs were ranked according to their R2 value. The best MR was used to determine the importance of the bio-indicators and their significance for explaining total and functional group richness patterns.

RESULTS

FUNCTIONAL GROUPS

The number of functional groups identified varied among dryland sites: eight functional groups in the Australian and WS-Savannah sites; nine in Caatinga and S-Europe, and 10 in the SW-Africa site (**Table 4.1**; **Table B.7 in Appendix B**). Generally, the identified functional groups were taxonomically and ecologically consistent. For example, all amphibians within a site tend to cluster (water dependency and high rates of fecundity), and the same pattern was observed in ungulates (large size, low fecundity), small mammals (small size, high fecundity), and small lizards, geckos and skinks (small size, low fecundity and often viviparous or ovoviviparous reproduction).

ECOLOGICAL NICHE-BASED MODELS AND SPECIES RICHNESS PREDICTIONS

The average accuracy of ecological models was high (0.7< TSS< 0.999) for all species and drylands, with the exception of Caatinga (0.5<TSS<0.955) (**Table B.8 in Appendix B**). Distribution patterns of species richness of functional groups were spatially heterogeneous within each dryland (**Fig. 4.1; Fig. B.3 in Appendix B**).

Table 4.1 - Functional groups identified in each dryland and functional strategy of each group.

Dryland	Group	Functional strategy
Australian	Ecto_MeEOO	Ectotherms with EOO: 1<EOO< 5 million km^2
	Ecto_SmBS	Ectotherms with body size < 30 cm
	Ecto_SmEOO	Ectotherms with EOO < 1 million km^2
	Ecto_MeFEC	Ectotherms with fecundity < 5 eggs
	LgBS	Body size > 30 cm
	MeFEC	Fecundity < 5 eggs
	SmBS	Body size < 30 cm
	Water	Water dependent species
Caatinga	Ecto_LgEOO	Ectotherms with EOO > 5 million km^2
	Ecto_MeBS	Ectotherms with body size: 30 <BS< 100 cm
	Endo_LoFEC	Endotherms with fecundity = 1 egg
	Endo_MeBS	Endotherms with body size: 30 <BS< 100 cm
	Endo_MeFEC	Endotherms with fecundity < 5 eggs
	SmBS	Body size < 30 cm
	Water_LgEOO	Water dependent species with EOO > 10 million km^2
	Water_SmEOO	Water dependent species with EOO < 5 million km^2
	Water_HiFEC	Water dependent species with fecundity > 100 eggs
SW-Africa	Ecto_LgBS	Ectotherms with body size > 100cm
	Ecto_MeEOO	Ectotherms with EOO: 1 <EOO< 5 million km^2
	Ecto_MeFEC	Ectotherms with fecundity < 5 eggs
	Ecto_MeBS	Ectotherms with body size: 30 <BS< 100 cm
	Ecto_SmBS	Ectotherms with body size < 30 cm
	Endo_LoFEC	Endotherms with fecundity = 1 egg
	Endo_MeFEC	Endotherms with fecundity < 5 eggs
	Endo_SmBS	Endotherms with body size < 30 cm
	SmBS	Body size < 30 cm
	Water	Water dependent species

Table 4.1 - Continued.

Dryland	Group	Functional strategy
S-Europe	Ecto_SmBS	Ectotherms with body size < 30 cm
	Ecto_MeFEC	Ectotherms with fecundity < 10 eggs
	Endo_LgBS	Endotherms with body size > 100 cm
	Endo_LgEOO	Endotherms with EOO > 10 million km^2
	MeBS	Body size: 30 <BS< 100 cm
	Endo_MeFEC	Endotherms with fecundity < 10 eggs
	Endo_SmBS	Endotherms with body size < 30 cm
	Water_HiFEC	Water dependent species with fecundity > 100 eggs
	Water_MeFEC	Water dependent species with fecundity < 100 eggs
WS-Savannah	Ecto_LgBS	Ectotherms with body size > 100 cm
	Ecto_MeBS	Ectotherms with body size: 30 <BS< 100 cm
	Ecto_SmBS	Ectotherms with body size < 30 cm
	Endo_MeBS	Endotherms with body size: 30 <BS< 100 cm
	Endo_LoFEC	Endotherms with fecundity = 1 egg
	Endo_MeFEC	Endotherms with fecundity < 15 eggs
	Endo_SmBS	Endotherms with body size <30 cm
	Water	Water dependent species

CONTRASTING BIOLOGICAL INDICATORS AND SPECIES RICHNESS PREDICTIONS

The All of the 27 bio-indicators were significantly correlated with at least one species richness group, either total or functional (**Table 4.2; Table B.9 in Appendix B**). For Caatinga, the only significant model was retrieved for the total species richness (**Fig. 4.1**). Statistically significant models were obtained in the remaining drylands only with functional groups, with the number varying between nine bio-indicators in S-Europe to 50 in WS-Savannah (**Table 4.2**). The mean TRMM Rainfall and mean SM (both cyclic fraction and vegetation year) were the most frequent (57%) bio-indicators exhibiting significant relationships (R2 higher than 0.25, except in Caatinga) with species richness across drylands (**Table 4.2** and **Fig. 4.2**). The TRMM Rainfall (both cyclic fraction and vegetation year) exhibited more significant relationships with species richness in S-Europe in comparison to the SM, while the opposite pattern was observed in SW-Africa. The strongest relationships (R2 higher than 0.40) between bio-indicators and species richness were observed between the variability of TRMM Rainfall in SW-Africa.

The dryland exhibiting most frequent significant relationships with analysed bio-indicators was the WS-Savannah (85% of bio-indicators).

The functional groups encompassing vertebrates of small body size (including either ectotherms or endotherms) were the ones that exhibited most often significant relationships with bio-indicators across drylands (**Table 4.2; Table B.9 in Appendix B**). In particular, the ectotherms of small body size in the WS-Savannah were significantly related with the majority of bio-indicators (81% of bio-indicators).

There is general spatial agreement between the distribution of areas of greater species richness and areas of high values for the bio-indicators showing mean values and respectively low values for the variability indicators, and the pattern was consistent across drylands (**Fig. 4.1; Fig. B.3 and B.4 in Appendix B**).

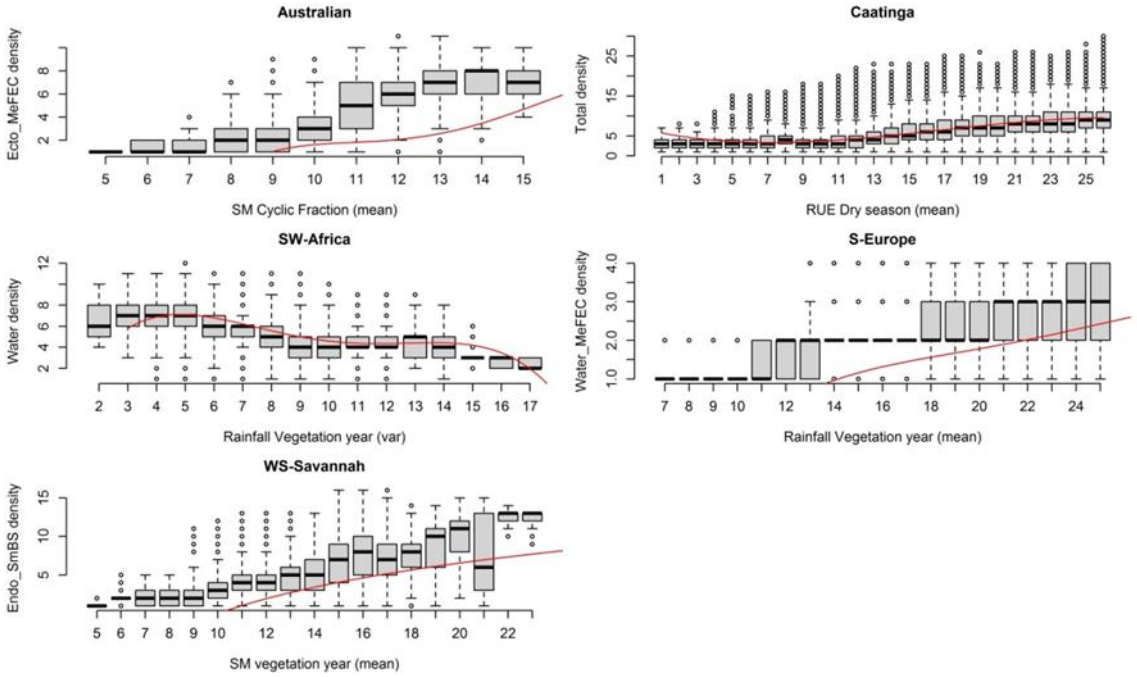

Fig. 4.2 - Relationships between functional groups and biological indicators. Averages and ranges of variation of functional groups density in all observed values of the corresponding bio-indicator. Represented functional groups are: Ecto_MeFEC - Ectotherms with fecundity < 5 eggs; Water - Water dependent species; Water_MeFEC - Water dependent species with fecundity < 100 eggs; Endo_SmBS - Endotherms with body size < 30 cm. Represented bio-indicators are: SM Cyclic Fraction (mean) - Soil Moisture Cyclic Fraction (mean); RUE Dry season (mean) – Rain Use Efficiency Dry season (mean); SM vegetation year (mean) – Soil Moisture vegetation year (Mean). SW-Africa: South-western Africa; S-Europe: Southern Europe; and WS-Savannah: West Sudanian Savannah.

Table 4.2 - Significant regression (R2) scores between species richness of functional groups and biological indicators. fAPAR, rainfall, RUE, SM and SMUE are coded according to the aggregations of different productivity periods. The different productivity periods correspond to the cyclic fraction (cyfr), dry season (dry) and vegetation year (veg). In addition, the mean length of the vegetation season (Lveg) was used. All bio-indicators were temporally aggregated between 2002-2012 based on the mean (M) and variation (V) statistics (Lveg only mean). Codes of functional groups are presented in Table 4.1.

		Australian				Caatinga	SW-Africa							S-Europe				WS-Savannah				
		Ecto SmBS	Ecto MeFEC	Ecto SmEOO	Water	Total	SmBS	Ecto MeFEC	Ecto LgBS	Endo LoFEC	Water	Endo SmBS	Endo MeFEC	Endo LgEOO	Water MeFEC	MeBS	Ecto SmBS	Endo SmBS	Endo MeBS	Ecto SmBS	Endo MeFEC	Ecto MeBS
fAPAR cyfr	M																	0.27	0.3	0.46		0.3
	V																			0.3		
fAPAR dry	M																	0.25	0.29	0.4		
	V						0.25													0.37		
fAPAR veg	M																	0.31	0.33	0.46		0.29
	V						0.27													0.33		
Rain cyfr	M	0.44		0.32	0.26									0.31	0.39	0.27	0.26	0.4	0.36	0.52	0.33	0.3
	V						0.41	0.45	0.45	0.46	0.46	0.43	0.45									
Rain veg	M	0.4		0.31	0.27									0.37	0.41	0.33	0.3	0.4	0.36	0.52	0.33	0.3
	V						0.4	0.46	0.45	0.46	0.47	0.44	0.45									
RUE cyfr	M	0.26	0.32																	0.25		
	V																			0.26		
RUE dry	M					0.3													0.26	0.34		
	V																			0.36		
RUE veg	M																			0.33		
	V																			0.31		
SM cyfr	M	0.4	0.55				0.31	0.26	0.26	0.26	0.26	0.25	0.26					0.31			0.25	0.26
	V	0.34	0.32				0.26	0.25		0.25	0.25											

Table 4.2 - Continued.

		Australian				Caatinga	SW-Africa							S-Europe				WS-Savannah				
		Ecto SmBS	Ecto MeFEC	Ecto SmEOO	Water	Total	SmBS	Ecto MeFEC	Ecto LgBS	Endo LoFEC	Water	Endo SmBS	Endo MeFEC	Endo LgEOO	Water MeFEC	MeBS	Ecto SmBS	Endo SmBS	Endo MeBS	Ecto SmBS	Endo MeFEC	Ecto MeBS
SM veg	M	0.36	0.52				0.35	0.3	0.3	0.29	0.29	0.29	0.29			0.26		0.34		0.33	0.3	0.28
	V	0.29																				
SMUE cyfr	M																		0.27	0.38		
	V																			0.29		
SMUE dry	M																		0.29	0.4		
	V																			0.37		
SMUE veg	M																		0.28	0.4		
	V						0.25													0.32		
L veg	M																	0.29	0.3	0.42		

DISCUSSION

This work presents a first evaluation of the ESA Diversity II bio-indicators for describing biodiversity patterns in drylands. It provides a comprehensive analysis of their correlation with the modelled spatial patterns of species richness (total and functional groups), and identifies suitable bio-indicators for describing distribution patterns of terrestrial vertebrates in drylands. Nonetheless, technical limitations constricted the analyses and possibly influenced results obtained and consequent interpretations. Herein, we pinpoint these technical limitations and possible implications to our work. We will argue that the derived bio-indictors have the potential to be effectively used in biodiversity research, depending on the targeted area or species group.

TECHNICAL LIMITATIONS AND POSSIBLE IMPLICATIONS

Key biological traits affecting physiological tolerances contribute to setting species environmental niches (Araújo et al. 2013). As such, representing species by their biological traits allows a better understanding of their relationship with the environment. However, this might be challenging due to the general lack of information on species' biological traits, which contributes to uncertainty in the functional groups identified in the present study. For instance, the inclusion of physiological traits directly linked to species survival in drylands (e.g., water balance, metabolic rates, or thermal limits) should increase the ability to discriminate functional groups. To overcome the lack of ecophysiological traits, we have included indirect biological traits known to be linked with species adaptive capacity in drylands (e.g., Rodríguez and Ojeda 2014; Vale and Brito 2015). Additionally, an upper limit was set to the number of groups that could be created to avoid producing many groups characterized by few biological traits. Overall, the consistencies in the identified functional groups across drylands suggest that the retrieved groups have a coherent biological meaning.

To fully assess species-environment relationships, ecological niche models should include the complete species' environmental range (Thuiller et al. 2004). However, high resolution distribution data was mostly unavailable for global ranges of the species under study. To overcome such problem, continental models were built at 10x10km resolution, which may have overestimated local species distributions and miss finer distributional details or local distribution gaps (Vale et al. 2014). The distinct spatial resolutions of the available eco-geographical variables used for modelling purposes

(1x1 km) and of bio-indicators (300 m) implied upscaling the resolution of bio-indicators (to 1x1 km) and to downscale the projections of continental models (10x10 km) to the drylands (1x1 km). These procedures may have also contributed to overestimation of distributions across analysed drylands. Despite the increase in uncertainty, spatial biases are expected to be constant throughout analysed drylands. Downscaling is a valid method to capture general environmental gradients and to predict species occurrence at finer resolutions (Araújo et al. 2005). The spatial resolution used in this study represents a compromise between the accuracy of the bio-indicators and uncertainty in ecological niche-based modelling.

Potential correlations between ecogeographical variables (regional set) and biological indicators might constitute an additional limitation since EGVs and biological indicators give a measure of precipitation patterns and land-cover (Globcover 09) and biological indicators were derived from the MERIS satellite. Yet, very few correlations were found between EGVs and biological indicators throughout drylands. For instance, no significant correlations between EGVs and biological indicators were observed in Southern Europe, which is probability related to the high amount of human pressure in the region (CIESIN-FAO-CIAT 2005). Relationships between bio-indicators and modelled species richness were inconsistent among drylands. In Caatinga, correlations were found only with total species richness, while in the WS-Savannah significant relationships were observed with almost all functional groups. The quantity, quality and source of the observational data used for building ecological models may be related to the lack of congruence among drylands. For assessing species richness patterns in functional groups, ecological models were based on presence data from GBIF in all drylands. However, the number of observations per taxa and their spatial distribution might have influenced models' accuracy. In Caatinga, low sample size of observations per taxa probably resulted in overall low model quality and biases in species richness predictions by functional group (**Fig. B.3 in Appendix B**). In WS-Savannah, available high resolution data was used for addressing weakness and fill gaps in GBIF data distribution, resulting in high number of records per species more evenly distributed across the study area. Larger number of records available per species collected over regular sampling intervals has been associated to more accurate predictions of species ranges (Feeley and Silman 2011). The high quality of models obtained for WS-Savannah allowed capturing relationships with almost all bio-indicators. Yet, the correlation between the total species richness and Rain Use Efficiency observed in Caatinga (**Fig. 4.1 and 4.2; Table B.9 in Appendix B**) suggested that increasing the number of species analysed might be important for overcoming sampling biases and to

capture general patterns. As such, we assume the limitations and implication of the GBIF dataset, particularly in Caatinga. Notwithstanding, high accuracy models were predicted for the remaining drylands, for which relationships with bio-indicators were clearly detected.

ASSESSMENT OF BIOLOGICAL INDICATORS FOR TERRESTRIAL VERTEBRATES IN DRYLANDS

Bio-indicators directly related with water availability (TRMM Rainfall and SM, both means and variation coefficient of cyclic fraction and vegetation year) were the most retrieved indicators with significant correlations with species richness in all drylands, with the exception of the Caatinga site. Relations were found with various types of functional groups, though water dependent species in particular were always associated with TRMM Rainfall and/or SM indicators, as expected. Functional groups comprising amphibians presented greater species richness in areas of high rainfall values or SM availability, in the Australian, SW-Africa and S-Europe drylands (**Fig. 4.1; Fig. B.3 and B.4 in Appendix B**). Amphibians are closely related with water availability, due to their physiology and their dependence on water during the initial life-cycle stages, and rainfall plays a vital role in the long-term amphibian abundance and distribution, especially in drylands (Kupferberg et al. 2012; Ocock et al. 2015). Other functional groups were associated to water availability bio-indicators (**Table 4.2, Fig. 4.1**), encompassing ecto- and endotherms, small to larger sized taxa, different reproductive strategies, and varying extents of occurrence. The positive relationships that were obtained between water availability bio-indicators and functional groups support that the geographical variation in rainfall is a major factor related to the distribution of multiple taxa (Brito et al. 2011).

According to our results, the bio-indicators most related to productivity (fAPAR, RUE and SMUE) had a low performance for explaining vertebrate species richness in the assessed drylands. The fAPAR was the bio-indicator with the lowest number of significant relationships with species richness. RUE and SMUE, two bio-indicators derived from fAPAR estimates and water availability variables, also revealed relatively low relationships with faunal biodiversity. These results may be explained by the bio-indicators per se, by the high spatial details that they reflect, and/or by anthropogenic interference. For example, the high spatial resolution of fAPAR incorporates finer details of the local distribution of water availability (e.g., related to hydrology and soil properties) than the ecological modelling approaches for the vertebrate species

distributions. Furthermore, RUE or SMUE indicators may be less related to the modelled species richness than pure rainfall data, as they reflect the NPP rate in relation to rainfall and SM, respectively. Although the NPP is related to rainfall itself, it is also highly dependent on local to regional environmental properties (e.g., soil nutrients, water tables, etc.), whereas the species richness modelling was based, among other factors, on direct rainfall estimates and done at a coarser scale, as already mentioned. Accurate distribution data at local level is scarce and further studies are needed to assess relationships between functional groups and biological indicators at smaller geographical scales. Lastly, human activities affecting land use/cover (e.g., farming, pasture and urbanisation) need to be taken into account when analysing relationships between productivity and biodiversity distribution patterns.

SMALL BODY SIZE FUNCTIONAL TRAIT ACROSS DRYLANDS

Small body size is clearly an important biological trait for shaping vertebrate species distribution patterns in drylands. Independently of the thermoregulatory behaviour, functional groups encompassing small body size taxa were better predicted by bio-indicators across drylands, particularly water availability related bio-indicators (TRMM Rainfall and SM). While rainfall is positively correlated with food availability, which indirectly affects reproductive success (Sarli et al. 2015), body size is correlated with physiological and fitness characters and affects the structure and dynamics of food webs, and other ecological networks (Blanckenhorn 2000; Woodward et al. 2005). Previous studies have found that biodiversity distribution of small mammals was found closely related with precipitation regimes in drylands of South America (Chillo et al. 2015) and in the Middle-East (Sarli et al. 2015). In the Sahara-Sahel region, functional groups encompassing small body size taxa were recently identified as the most vulnerable to future climate change, particularly to precipitation change (Vale and Brito 2015). Accordingly, functional groups of small body size taxa might be similarly vulnerable to future climate change in the selected drylands or in different regions that were not analysed in this study. As such, bio-indicators (or perhaps directly rainfall indicators) might be used not only for monitoring functional groups encompassing small body size taxa, but also for climate change assessments in drylands.

CONCLUSIONS

This study revealed the potential of the Diversity II bio-indicators in providing estimations of water availability and primary productivity that could be contrasted with major patterns of biodiversity. More studies should focus on the application of these bio-indicators. Overall, raw variables depicting water availability (like TRMM Rainfall and SM) exhibited closer relations with modelled vertebrate species richness in drylands, in comparison to estimates of primary productivity or RUE and SMUE. On the one hand this may be due to the much finer spatial scales of these bio-indicators, which reveal spatial variability that cannot be related to the coarser modelling parameters. On the other hand, given that water resources are usually scarce and temporally limited in drylands, water availability per se might be the main driver of biodiversity patterns in drylands (Davis et al. 2013; Vale et al. 2015). Yet, primary productivity related bio-indicators are apparently more informative for specific functional cases. As such, our results do not suggest to discard the application of these bio-indicators, but rather to take all into consideration when assessing biodiversity patterns. The methodological approach conducted in this study can be extrapolated to other drylands, since the bio-indicators that were used are freely accessible for 22 major drylands globally distributed (http://www.diversity2.info/products/). Consequently this work can serve as an example for other studies focused on the relationships between dryland biodiversity and primary productivity, where tests should also be performed at coarser spatial resolutions, i.e., by adapting the spatial resolution of the bio-indicators to that of the major other variables used in the species modelling approaches. Additionally, given that the full archive of ENVISAT-MERIS data (used for deriving fAPAR estimates), TRMM rainfall data and ESA CCI SM data are publically available for the entire globe, these bio-indicators should be tested in different ecosystems.

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Mechaouba valley, Mauritania

Photo: JC Brito

CHAPTER V

Remote Sensing and landscape features for the assessment of local biodiversity patterns in the West Sahara-Sahel

I fell in love; With a beautiful highway; This used to be real estate; Now it's only fields and trees; Where, where is the town; Now, it's nothing but flowers; The highways and cars; Were sacrificed for agriculture; I thought that we'd start over; But I guess I was wrong; Once there were parking lots; Now it's a peaceful oasis; You've got it, you've got it; (…); Don't leave me stranded here; I can't get used to this lifestyle

Talking Heads, (Nothing but) flowers (1988)

Article III - Revealing unknown land cover heterogeneity in the West Sahara-Sahel and its implications for biodiversity conservation

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ABSTRACT

Accurate categorization of land cover is considered crucial for achieving Aichi Biodiversity Targets. The Sahara-Sahel comprises high biodiversity levels and habitat heterogeneity that usually remain undetected in available global land cover maps. A 30x30 m resolution land cover map of the West Sahara-Sahel was developed through a stepwise methodology for land cover assessment, improving the current land cover information for the region. GPS field-collected control points (n=46,545) and associated descriptive traits were grouped by Hierarchical Cluster Analyses (HCA). Resulting groups were used for Landsat image classification. Independent control points (n=9,408) suggested a robust regional classification (83.9% correctly classified) of land cover. The HCA provided an observer-independent selection of 14 land cover classes. The final map, composed by a total of 18 classes, constitutes framework data for mapping local biodiversity distribution and for improving the effectiveness of solutions concerning biodiversity conservation and management of natural resources for local human populations.

Keywords: Arid regions; Biological conservation; Ecoregions; habitat heterogeneity; Remote Sensing; Landsat.

INTRODUCTION

Remote Sensing (RS) has proven to be an effective tool for conservation by detecting, mapping and predicting key drivers of biodiversity change across the globe (Yang et al. 2013; Pettorelli et al. 2016a; Rose et al. 2015; Willis 2015). Land cover (LC) is one of the most important RS-derived variables, being recently proposed as one of the 10 critical variables to monitor progresses towards the Aichi Biodiversity Targets (Skidmore et al. 2015). Categorizing LC provides crucial landscape information that can be used for further monitoring, management and conservation (Yu et al. 2015; Pettorelli et al. 2016b).

The necessity of LC products, highlighted by the Convention on Biological Diversity, has resulted in several available global LC maps with spatial resolution from 300m to 10km, such as the MODIS LC product (Friedl et al. 2010) and the European Space Agency (ESA) GlobCover maps (http://www.esa-landcover-cci.org/?q=node/158). With the aim of increasing spatial resolution of LC maps, allowing fine-scale analyses of LC complexities (Yu et al. 2015), 3 global LC maps were recently derived at 30x30m resolution: the global LC from the United States Geologic Survey (USGS; http://landcover.usgs.gov/glc/), the Finer Resolution Observation and Monitoring-Global Land Cover (FROM-GLC; Gong et al. 2013), and the Global Land Cover 30m (GLC30; Chen et al. 2015). Despite their increased spatial resolution, inadequate accuracy and frequent misclassifications have been detected in different ecoregions across the globe (Tropek et al. 2014; Yu et al. 2015). These constraints hamper the assessment of landscape information and its relations to possible biodiversity changes, especially in remote regions where field investigations are difficult to perform (Campos et al. 2012; Duncan et al. 2014).

The heterogeneity of the remote Sahara desert and the arid Sahel ecoregions of Africa are usually undetected in available global LC maps. For instance, the ESA GlobCover maps and the GLC30 (Chen et al. 2015) illustrate extensive bare areas across the West Sahara-Sahel that clearly misrepresent important landscape features, such as mountains and the associated biodiversity hotspots (Brito et al. 2016). This denotes a major limitation for local biodiversity conservation and management, particularly in a region acknowledged by many as mostly homogenous that exhibits low biodiversity in comparison to other regions across the globe (Durant et al. 2012). However, the West Sahara-Sahel comprises high biodiversity levels and increased local endemic rates

distributed across highly heterogeneous habitats (Brito et al. 2014) due mostly to 3 reasons. First, it encompasses the limit between the Palearctic and Afro-Tropical biogeographical regions, resulting a in a biogeographic crossroad of increased species richness (Brito et al. 2016). Second, the West Sahara-Sahel constitutes a major latitudinal biodiversity corridor due to the moderate climate influenced by the Atlantic Ocean (Brito et al. 2014). Third, the region exhibits high LC heterogeneity, including different dune types (e.g., mobile and fixed dunes with diverse soil colourations and vegetation cover), rocky regions (e.g., rock outcrops, rocky plateaus and gravel floodplains), and mountain rock pools that have been identified as local biodiversity hotspots (Vale et al. 2015).

The evident misrepresentation of LC heterogeneity in deserts and arid regions by the available global LC maps represents a major challenge for informative RS-derived LC products. Although RS techniques are particularly advantageous for acquiring information in remote regions, their potential have been largely unexplored and few local RS-derived variables are available in these areas (e.g., Haas et al. 2009; Fensholt et al. 2013). We aimed to overcome a major knowledge gap concerning Sahara-Sahel LC heterogeneity by: 1) creating a RS-derived LC map (30x30m resolution) of the West Sahara-Sahel based on an extensive dataset of field control points; 2) developing an iterative stepwise methodology for LC class selection and LC classification; 3) improving the current regional LC mapping. This work demonstrates that increased efforts on LC mapping at local scales provide relevant and new landscape information that can be used for managing local natural resources and in future conservation frameworks focused on the unique and threatened biodiversity in a remote and poorly studied region.

METHODS

STUDY AREA

The study area encompasses an area of approximately 1,979,127 km2, varying between 28°N, 14°N, 17°W and 4°W, comprising southern Morocco, south-western Algeria, full extent of Mauritania, south-western Mali and north-eastern Senegal (**Fig. C.1 in Appendix C**). We adjusted the study area limits to the spatial coverage of the field control points, covering 4 major ecoregions (according to Olson et al. 2001).

Altitude varies from approximately 9 m on the Senegal River valley to 1060 m in the southern Anti-Atlas in Morocco.

FIELD DATA

We collected a total of 46,545 field control points (**Table 5.1**) during 4 overland expeditions to Mali, Mauritania, and Morocco between 2011 and 2014 (**Fig. C.1 in Appendix C**). We separated the points in the field according to 6 associated habitat-descriptive traits: 1) Water availability: absence, seasonal or permanent water; 2) Soil texture: clay, sand, stones, gravel, rocks or salt; 3) Soil compaction: hard, loose or unknown; 4) Soil coloration: white, grey, yellow, orange, black, brown or unknown; 5) Slope: <30º or >30º; and 6) Vegetation cover: grassland, trees, isolated tree, woodland, cropland or no vegetation. We determined the habitat traits of each control point based on inquiries to local people (water availability) and visual evaluations. We gathered the geographic coordinates of control points from a Global Positioning System (GPS) receptor on the datum WGS-1984.

Table 5.1 - Total number and number of field control points per class used for training the classification algorithm and for validating the final classification.

Classes[1]	Training (n)	Validation (n)	Total (n)
COMPSO	5387	1347	6734
SOIL_R	3328	832	4160
GRAS	4666	1166	5382
ROPL	661	165	826
YDUN	4154	1038	5192
COMPS	3811	953	4764
SPAN	180	45	225
SAVA	1578	394	1972
ROCK	2572	643	3215
GRFL	3774	944	4718
GSFL	3516	879	4395
ODUN	2449	612	3061
WDUN	1148	287	1435
CROP	413	103	516
Total	37,687	9408	46,595

PROCESSING OF SATELLITE IMAGES

We obtained satellite images (30x30 m resolution) from Landsat 8 series through the Global Visualization Viewer (GLOVIS; http://glovis.usgs.gov/) of the United States Geological Survey (USGS). We selected the temporal resolution of the Landsat images according to the periods in which the GPS control points were collected. However, given the failure of the Landsat 5 Thematic Mapper (TM) in November of 2011 (Yu et al. 2015), only 2 temporal periods were covered (January-February and November-December of 2014). We retained only images with less than 10% of cloud cover for analyses. The final dataset comprised 190 (95 Landsat scenes per each temporal period) satellite images (**Table C.1 in Appendix C**). The Landsat images were georeferenced by the United States Geological Survey (http://landsat.usgs.gov/) and all the analyses were developed on the datum WGS-1984. Atmospheric corrections and haze removal procedures were conducted for all extracted images using the calibration coefficients of the ATCOR tool of PCI Geomatica v. 2015 (Richter 1996, 2010). Six Landsat 8 bands were selected for further land cover classification (Zhu and Woodcock 2014): band 2 (blue); band 3 (green); band 4 (red); band 5 (Near infrared-NIR); band 6 (short-wave infrared 1 -SWIR 1); and band 7 (short-wave infrared 2 -SWIR 2). We built mosaics for the entire study area for each of the selected bands and the 2 temporal periods. We removed margin effects between overlapping scenes from the mosaics using the OrthoEngine mosaicking tools from PCI Geomatica. Finally, we used the mosaics from the 2 different time periods to calculate a final mean mosaic, which was further integrated in supervised classifications.

SELECTION OF LAND COVER CLASSES

We grouped the control points into distinct LC classes according to the identified traits through a Hierarchical Cluster Analyses (HCA). We selected the HCA for identifying the LC classes independently from the field visual classifications. First, we calculated a pairwise distance matrix between control points using the package *cluster* from the R software v. 3.1.1 (R Core Team 2014). We excluded control points with identical habitat traits (replicates) from the matrix calculation and considered during the LC classification process. We selected the Gower distance as it allows calculations between different variable types (e.g., numerical and categorical variables; Gower 1971). We used the distance matrix as an input for the HCA, conducted using the R package *pvclust* and using 1,000 bootstrap replicates. The obtained clusters were assumed as distinct LC classes and we measured their spectral pairwise separability

by the Bhattacharyya Distance tests through PCI Geomatica. LC classes with low separability values (i.e., Bhattacharyya distance<1.90) were iteratively merged until we obtained a reasonable overall distance measure between the final set of classes (Schulz et al. 2010).

LAND COVER CLASSIFICATION

To ensure independent classification and validation procedures, we selected two datasets for each LC class, based on simple random stratified sampling (Foody 2002): one for training the classification algorithm (80%) and one for validating the final classification (20%). The random stratified sampling was performed in ArcGIS 10.1 (ESRI 2012). We conducted supervised classifications through PCI Geomatica with the training datasets and the mosaics using all algorithms implemented in the software. We evaluated the classification performance of validation datasets by the overall accuracy and Kappa coefficient measures (Landis and Koch 1977). A confusion matrix was also built, indicating the omission errors (i.e., Σ control points incorrectly attributed to the class/total number of control points attributed to the class), the commission errors (i.e., Σ control points incorrectly classified/total number of control points), the producer's accuracy (i.e., control points correctly attributed to the class/total number of control points attributed to the class) and the user's accuracy (i.e., control points correctly classified/total number of control points). We also verified the classification accuracy according to three major ecoregions: the Sahara (combining the Sahara desert, the North and South Saharan steppes and woodlands, the Atlantic Coastal Desert, the West Saharan mountain xeric woodlands, and the Saharan halophytics ecoregions), the West Sudanian Savannah and the Sahel (Sahelian Acacia savannah ecoregion). The Mediterranean Acacia-Argania dry woodlands and succulent thickets ecoregion was not considered since it occupied only 1% of the study area.

CLASSIFICATION CORRECTIONS

The spectral signals of some LC classes were confounded during preliminary classification essays, which produced misclassifications that were further confirmed by visual interpretation of the LC map. We observed misclassifications of rocky pixels as savannah mostly in the northern parts of the study area, and of water-bodies as vegetation (grasslands and savannah) or as rocky areas (gravel floodplains and bare rock) across all the study area. We applied specific protocols to the identification of

rock and water pixels, using local masking for cleaning erroneous savannah pixels and water indexes, respectively.

We applied a savannah mask for correcting misclassifications of rocky regions. We built the mask through the extraction of the savannah pixels from the final classification, whose extent was defined according to a southern latitudinal limit, based on the boundaries of the Sahelian Acacia savannah ecoregion (Olson et al. 2001). We conducted this process given our assumption that savannah habitats are not present north of the Sahel. For highlighting the erroneous savannah pixels, we reclassified the mask pixels (10^3 X their original value) and we consequently added on the final classification. We reclassified the identified erroneous savannah pixels into the value corresponding to the bare rock LC class. We conducted all the analyses concerning the construction of the savannah mask and correction of erroneous pixels in ArcGIS 10.1.

We identified water-bodies using the Automated Water Extraction Index (AWEI; Feyisa et al. 2014), which uses an arithmetic combination of spectral bands to enhance water from non-water pixels. We selected the AWEIsh since it was formulated for improving the accuracy of water detection by removing the effect of shadow pixels (Feyisa et al. 2014), a common limitation that usually lead to water overestimations in arid regions (e.g., shadows associated to dune lines; Campos et al. 2012). We calculated the index according to Feyisa et al. (2014) and we determined the water reclassification thresholds based on the water control points extracted in the field and following the procedures in Campos et al. (2012). Finally, we overlapped the water map composed by pixels with water and non-water on the previously calculated LC classification. We performed all the analyses related to the identification of water bodies in ArcGIS 10.1.

IDENTIFICATION OF SEPARATE CLASSES AND FINAL LAND COVER MAP

We identified 3 LC classes, namely paved roads, railroads and major urban areas, separately from the classification process (**Fig. 5.1**). This procedure was executed since their spectral signal was confounded with rocky LC classes (e.g., gravel floodplains, bare rock and rocky plateaus), which impeded their robust classification and decreased the overall classification performance. We defined main paved roads by GPS tracks extracted during the field expeditions. We manually digitized railroads and major urban areas from satellite images available in Google Earth (https://www.google.com/earth/). We then converted main paved roads, railroads and major urban areas to raster and added to the LC classification in order to obtain the final LC map. We conducted all the analyses using ArcGIS 10.1.

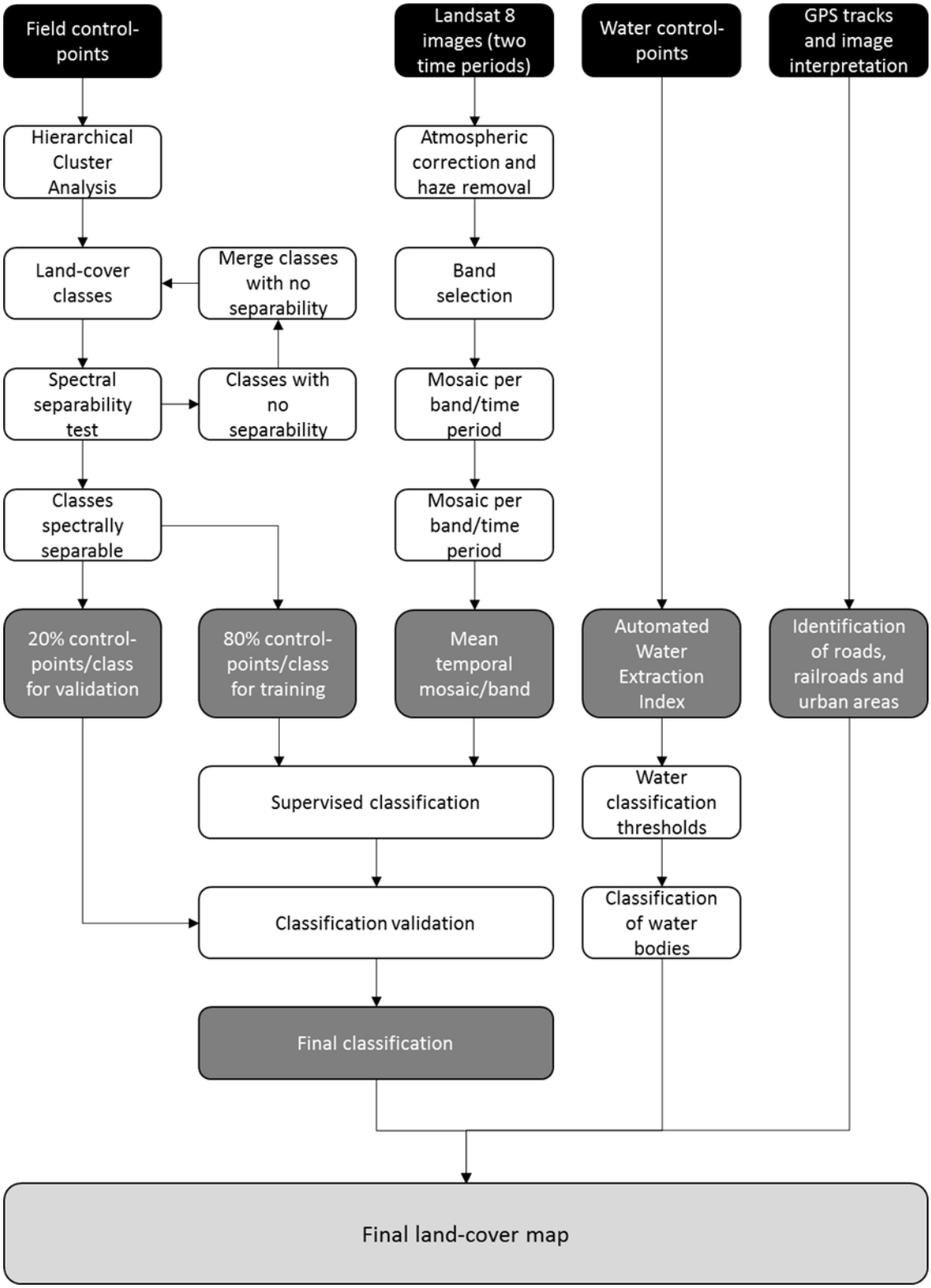

Fig. 5.1 - Overview of land cover classification analyses depicting primary inputs (black boxes), intermediary steps (white), outputs/inputs (dark grey) and final output (light grey).

RESULTS

LAND COVER CLASSES

The iterative HCA allowed the identification of 15 LC classes (**Fig. C.2 in Appendix C**). Water-bodies were excluded from further classifications and were classified following specific methodology (see Methods section). We identified the remaining 14 classes (see **Table C.2 in Appendix C** for details) according to the separation of clear clusters in favour to their branch relations. The mean Bhattacharyya Distance was high (1.95), indicating an overall spectral pairwise separability between all classes (**Table C.3 in Appendix C**). Most of the classes (n=9; YDUN, CROP, WDUN, ODUN, GRFL, GSFL, SAVA, SPAN and SOIL_R) were highly separable between at least 12 other classes. Overall, class GRAS had the lowest separability, registering low separability between 6 classes (COMPS, COMPSO, CROP, ROPL, ROCK and SAVA). The lowest separability value was verified between ROCK and ROPL.

LAND COVER CLASSIFICATION

The final classification was given by the Maximum Likelihood classifier using a total of 37,687 training control points (**Table 5.1**). According to the overall validation measures (**Table 5.2**), the classification performance was statistically high (Overall accuracy=83.9% and Kappa coefficient=0.822). Individually, 10 classes had more than 80% of correct classification (user accuracy) of which 9 had less than 20% of omission errors (**Table 5.2**). Orange and white dunes (ODUN and WDUN) had the highest correct classification values (96.6% and 94.8%), while grasslands (GRAS) had less than 70% of points correctly classified. The highest omission error rate was verified for rocky plateaus (ROPL), while salt pans (SPAN) had no omission errors. Significantly different LC classification accuracies ($\chi 2$; $p<0.001$) were obtained between ecoregions (**Table 5.3**). The Sahara was the most representative ecoregion and exhibited the highest classification accuracy (93%) while the Sahel retrieved lower accuracy (82%).

Table 5.2 - Classification confusion matrix for the selected 14 land-cover classes[1]. Columns indicate the number of validation control points/class that was correctly and incorrectly classified. Rows indicate the number of control points from all the available classes that were attributed to a particular class.

	COMPSO	SOIL_R	GRAS	ROPL	YDUN	COMPS	SPAN	SAVA	ROCK	GRFL	GSFL	ODUN	WDUN	CROP	Total (n)	Omission (%)	Accuracy (%)
COMPSO	1069	129	124	5	9	22	1	0	8	8	2	5	0	0	1382	25.6	74.4
SOIL_R	83	676	6	1	13	10	0	0	0	0	1	1	0	0	791	14.5	85.5
GRAS	128	15	814	12	22	0	1	16	57	34	1	1	0	9	1110	26.7	73.3
ROPL	12	0	39	121	0	0	0	6	48	6	0	0	0	0	232	47.8	52.2
YDUN	11	0	5	0	890	17	0	0	1	2	7	6	1	0	940	5.3	94.7
COMPS	0	2	70	1	13	867	0	0	4	1	5	7	8	0	978	11.3	88.7
SPAN	0	0	0	0	0	0	41	0	0	0	0	0	0	0	41	0.0	100
SAVA	13	0	22	0	0	0	0	351	0	0	0	0	0	11	397	11.6	88.4
ROCK	3	1	55	24	1	0	0	0	498	43	1	0	0	0	626	20.4	79.6
GRFL	7	6	5	1	7	0	1	0	17	809	45	1	0	0	899	10.0	90.0
GSFL	12	3	0	0	27	8	0	0	8	41	813	0	2	0	914	11.1	88.9
ODUN	1	0	0	0	22	25	0	0	2	0	4	591	4	0	649	8.9	91.1
WDUN	0	0	0	0	34	4	1	0	0	0	0	0	272	0	311	12.5	87.5
CROP	8	0	26	0	0	0	0	21	0	0	0	0	0	83	138	39.9	60.1
Total (n)	1347	832	1166	165	1038	953	45	394	643	944	879	612	287	103			
Commission (%)	20.6	18.7	30.2	26.7	14.3	9.0	8.9	10.9	22.6	14.3	07.5	3.4	5.2	19.4			
Accuracy (%)	79.4	81.3	69.8	73.3	85.7	91.0	91.1	89.1	77.4	85.7	92.5	96.6	94.8	80.6			

Table 5.3 - Number (n) of validation control points and percentage (%) of points correctly classified (CC) for the selected 14 land-cover classes[1] across three major ecoregions.

	Sahara	West Sudanian Savannah	Sahel
COMPSO	-	330 (81%)	1017 (79%)
SOIL_R	-	-	831 (80%)
GRAS	18 (6%)	159 (25%)	983 (78%)
ROPL	4 (75%)	-	132 (83%)
YDUN	520 (92%)	-	517 (79%)
COMPS	77 (62%)	-	868 (94%)
SPAN	10 (100%)	-	9 (67%)
SAVA	-	369 (95%)	-
ROCK	58 (50%)	19 (5%)	558 (83%)
GRFL	614 (93%)	1 (0%)	327 (72%)
GSFL	756 (95%)	-	106 (87%)
ODUN	367 (97%)	-	245 (96%)
WDUN	247 (94%)	-	40 (100%)
CROP	-	22 (18%)	79 (66%)
Total n points	2671	900	5737
Total n points CC	2448 (93%)	662 (74%)	4691 (82%)

[1] Classes without control points in a particular ecoregion are represented by "-". See codes of LC classes in Table C.2 in Appendix C.

CLASSIFICATION CORRECTION, SEPARATE CLASSES AND FINAL LAND COVER MAP

The applied savannah mask eliminated most of the misclassified savannah pixels, allowing a correct reclassification to bare rock (see example in **Fig. C.3 in Appendix C**). The AWEIsh identified most of the permanent water-bodies in the region (see example in **Fig. C.3 in Appendix**) and the selected threshold allowed the correct classification of almost 85% of permanent water control points (**Fig. C.4 in Appendix**). Contrarily, the AWEIsh failed in the detection of seasonal water-bodies, where the selected threshold allowed the correct classification of 7% of seasonal water control points (**Fig. C.4 in Appendix**). The GPS tracks and the visual interpretation of satellite images outlined the main paved roads, railroads and major urban areas (**Fig. C.5 in Appendix**). We added water-bodies, paved roads, railroads and urban areas to the previous classification, which resulted in the final LC map with 18 classes (**Fig. 5.2**). For each classified class, it was calculated the area proportion (**Table C.4 in Appendix**

C) and the total area (**Table C.5 in Appendix C**) through post-stratified estimation, in order to supress biases related with classification errors. The estimated proportions, the total estimated area and the standard deviation of the error-adjusted estimated area were calculated according to Olofsson et al. (2013). The final LC map (and control points) is available at (to be given after manuscript acceptance).

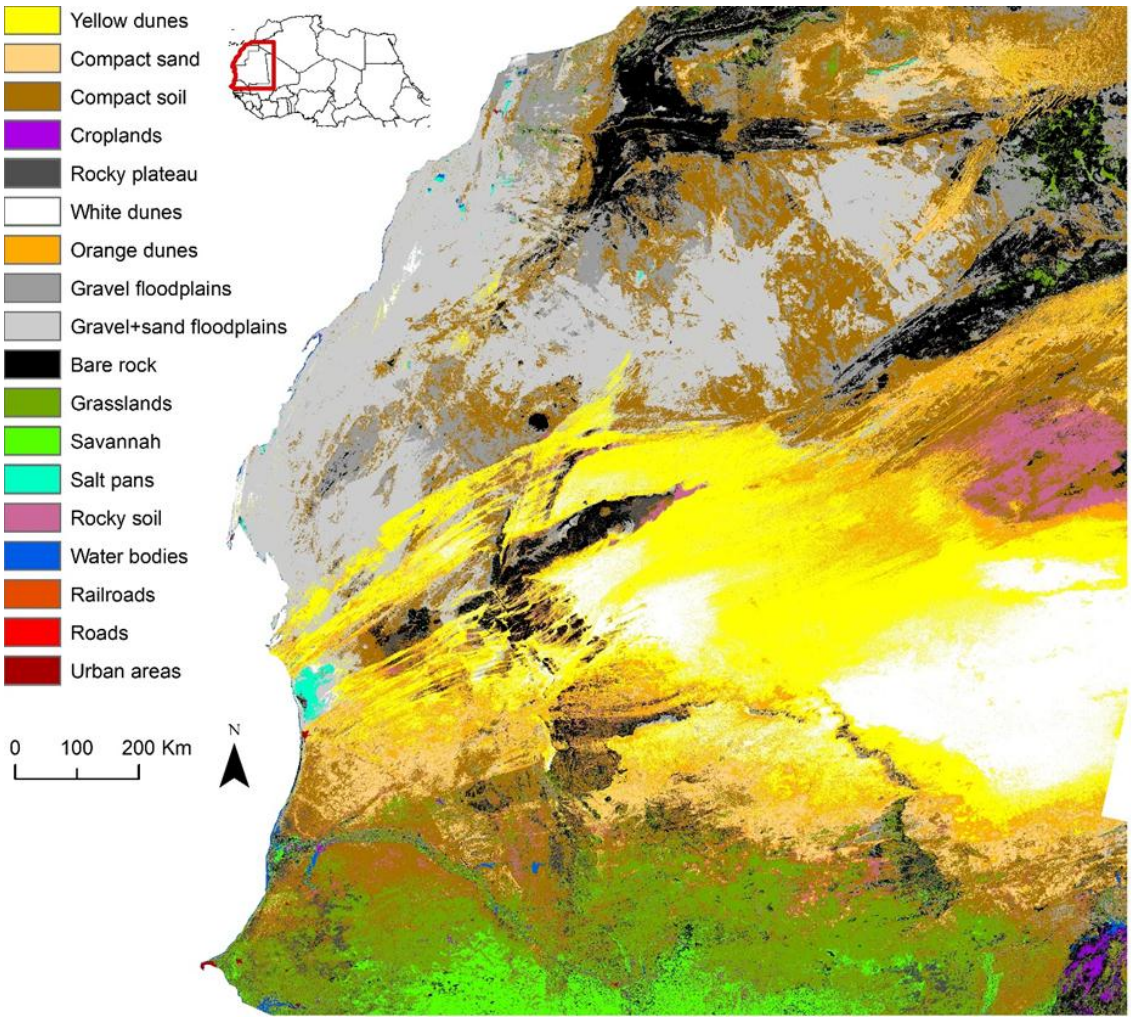

Fig. 5.2 - Final land cover map for the West Sahara-Sahel regions. The 18 land-cover classes are represented with different colours according to the legend.

DISCUSSION

SOURCES OF UNCERTAINTY IN LAND COVER CLASSIFICATION

Control points were mostly collected within the Sahara and Sahel ecoregions, thus caution is required when interpreting classifications in the Mediterranean and West Sudanian Savannah ecoregions. It was not possible to conduct a pre-established randomly selection of sampling sites (see Foody 2002) due to the large dimensions of the study area, the general remoteness, and the reduced accessibility to particular inland regions (e.g., eastern areas). Additionally, the spectral variability of the identified LC classes distributed in these ecoregions was not accounted during the training of the classification algorithm, which might prompt unassessed effects in the final classification. The restricted temporal resolution of Landsat series (one image/location every 16-days) associated to the Landsat 5 TM failure in November of 2011 (Yu et al. 2015) prevented full temporal coverage of the field extracted control points (2 temporal periods lacked satellite data). The limited temporal overmatch between satellite and field data might have constrained LC classification performance. The restricted temporal availability of Landsat series is known as its major drawback (Zhu and Woodcock 2014). Although this limitation may be surpassed by further data implementation (e.g., image fusion techniques), most satellite data needed for these analyses are publically unavailable.

LAND COVER MAP OF THE WEST SAHARA-SAHEL

The extensive fieldwork effort allowed collecting a large control point dataset that was crucial for classifying and validating a high resolution land-cover map of extensive arid and semi-arid regions. The existing dataset corroborated the essential role of field data for obtaining robust LC maps (Zhao et al. 2014). Moreover, the dataset can be useful for cross-validation of other global or regional LC maps, an important step for evaluating and comparing their current accuracy, which is difficult to accomplish since most of the available control points are based on visual interpretation of satellite images (Zhao et al. 2014). The hierarchical classification algorithm provided an observer-independent method for a priori selection of habitat classes; a frequent issue in LC categorization (Hansen and Loveland 2012). This methodology may improve future LC mapping by removing subjective decisions in class categorization and it

should be further explored in other global ecoregions. The classification corrections were crucial for obtaining classes that usually are difficult to classify, namely water bodies and non-natural features (Feyisa et al. 2014). Additionally, this step also allowed cleaning classification errors that are related to non-considered classes. For instance, the observed bare rock misclassifications in the northern regions were probably related with the natural geology of the mountains, usually composed by oxides of iron such as hematite and magnetite (Trompette 1973). The oxides of iron were not envisaged in the classification and were erroneously attributed to the savannah class, a problem solved with the filter application (see **Fig. C.3 in Appendix C**).

The West Sahara heterogeneity was represented more accurately in the derived LC map in comparison to available LC maps (see examples in **Fig. 5.3 and Fig. C.6 and C.7 in Appendix C**). The ecoregion is composed by different types of dunes and rocky habitats (see example in **Fig. 5.4**), classes that are normally misrepresented and coarsely classified as bare areas in available global LC maps (see **Fig. C.6 and C.7 in Appendix C**). Efforts in the collection of larger field datasets might allow a clear identification of these classes, as observed for the high accuracy classifications of different dune types (see **Table 5.2**). Still, the lowest separability value was verified between two rocky classes, bare rock (ROCK) and rocky plateaus (ROPL). Despite representing distinct habitats, these classes are geologically and spectrally similar, which impeded a clear classification even with the extensive current dataset. These two classes should be merged in the future for improving the overall classification accuracy.

Contrarily, the West Sahel heterogeneity in the derived LC map was apparently underrepresented in relation to global LC maps, despite the acceptable correct classification rate of the former. Such underrepresentation may be explained by the few resulting classes derived from the initial process of LC class selection. In comparison to the Sahara, the Sahel is subjected to an increase of average rainfall, amplifying coverage by complex vegetation structures, and displays distinct soil type compositions (Heumann et al. 2007; Frappart et al. 2009). The lowest separability observed between grasslands and different soil (compact sand and compact soil) and vegetation (croplands and savannah) classes may be representative of the Sahelian LC complexity. These LC complexities are reflected in the increase of spectral confusions between classes, which ultimately affect the accuracy of classifications (e.g., less than 70% of grassland control points correctly classified). A larger field dataset is required for improving the LC class selection and classification in the southern areas.

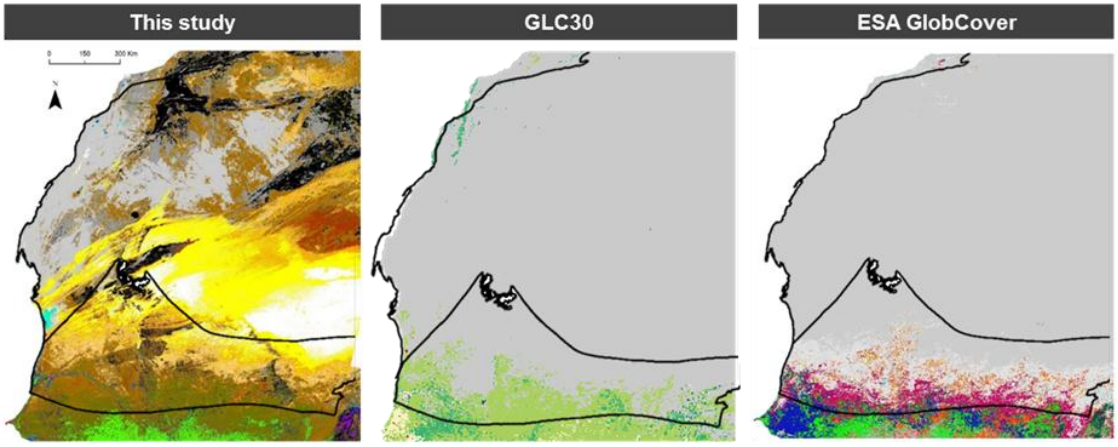

Fig. 5.3 - Visual contrasts between land cover maps derived in this study (left map), the GLC30 (center map) and the ESA GlobCover 2009 (right map). Land cover classes are represented in different colours. The most representative class in GLC30 and ESA GlobCover, bare areas, is represented in grey in both maps.

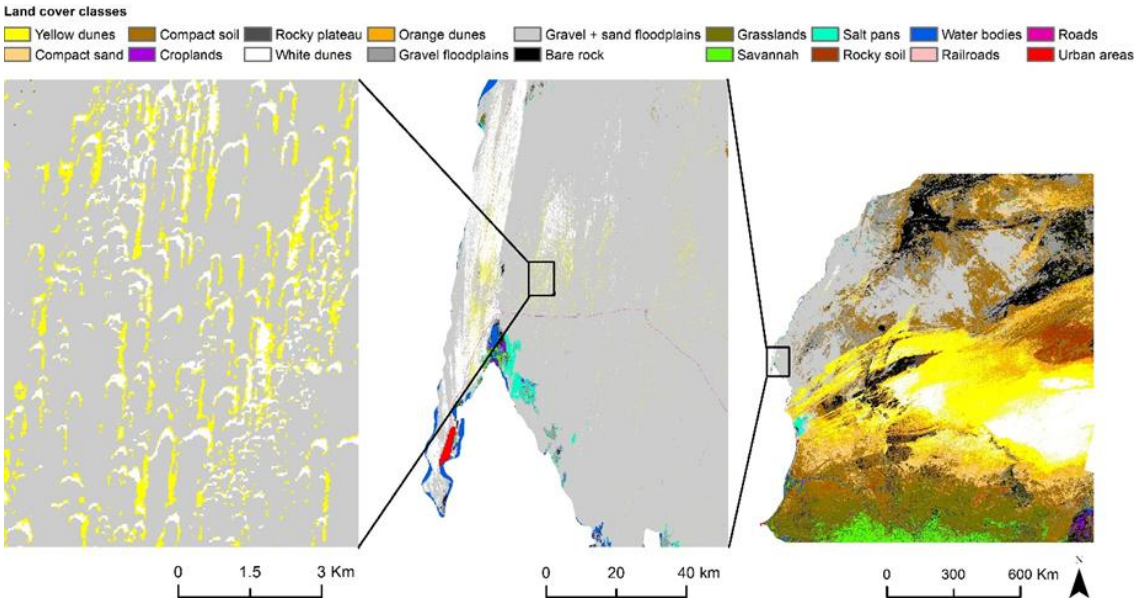

Fig. 5.4 - Example of the detailed identification of different types of dunes included in the final land cover map. The finest zoom shows the land cover classification details of Timazzine dunes (Morocco).

IMPLICATIONS FOR CONSERVATION

The obtained LC map constitutes framework data for mapping local biodiversity distribution and improving the effectiveness of conservation solutions, especially in threatened species persisting across the Sahara-Sahel in isolated populations (Brito et al. 2014). For instance, it could help locating potential suitable areas for the Critically Endangered addax (*Addax nasomaculatus*) in Mauritania. The original range of this

iconic mammal declined by 99% and presently it is known only from a population located in Niger (Duncan et al. 2014; Durant et al. 2014), but a likely small and isolated group has been suggested to persist in remote inland areas of Mauritania (International Union for Conservation of Nature 2013). The high resolution LC map may be used to identify areas in Mauritania exhibiting similar habitat characteristics to the Nigerian areas where addax populations currently persist (i.e., fixed sands and flatter areas within and between dune fields that support perennial vegetation; International Union for Conservation of Nature 2013), and thus, indicating the most relevant areas for future field surveying (**Fig. 5.5**). In the case of the West-African crocodile (*Crocodylus suchus*), relict populations persist in water-bodies across southern Mauritanian mountains and individual dispersal between rock-pools through seasonal streams that are formed during the rainy seasons has been reported (Campos et al. 2012; Velo-Antón et al. 2014). The water availability depicted in the LC map (**Fig. C.8 in Appendix C**) provides relevant data about occupied habitats and possible dispersal pathways that are useful to understand regional population connectivity patterns (see Supporting Information). These water-bodies are local biodiversity hotspots in need of global attention (Vale et al. 2015), but they are hard to detect in the field due to their general small size and remoteness. The high resolution of the LC map may be used to locate additional mountain rock-pools.

The LC map provides accurate information about landscape structure in a region where resource assessment represents a major priority. The continuous exploration and degradation of natural resources represents a key factor enhancing poverty and insecurity (Brashares et al. 2014), and increasing social tensions and violent conflicts in the Sahara-Sahel transition zone have been reported (Abdalla 2009). The LC map could be used for assessing and conserve important habitats for biodiversity that also secure beneficial ecosystem services for local human populations (see Turner et al. 2012). Climate change predictions for the region represents a main issue (Loarie et al. 2009) that may influence natural resources availability (e.g., water availability decrease and desertification) and force recurrent human migrations (Maestre et al. 2012). Detailed LC mapping is crucial for assessing the current habitat composition of arid regions and to understand how climatic changes will possibly affect resource availability and ultimately the adaptation of local human populations (Intergovernmental Panel on Climate Change 2014). The derived LC map constitutes a status map of current LC that can be used by local governmental entities and/or autonomous agencies, such as UNESCO or UNCCD, for future decision making in the management of important natural resources.

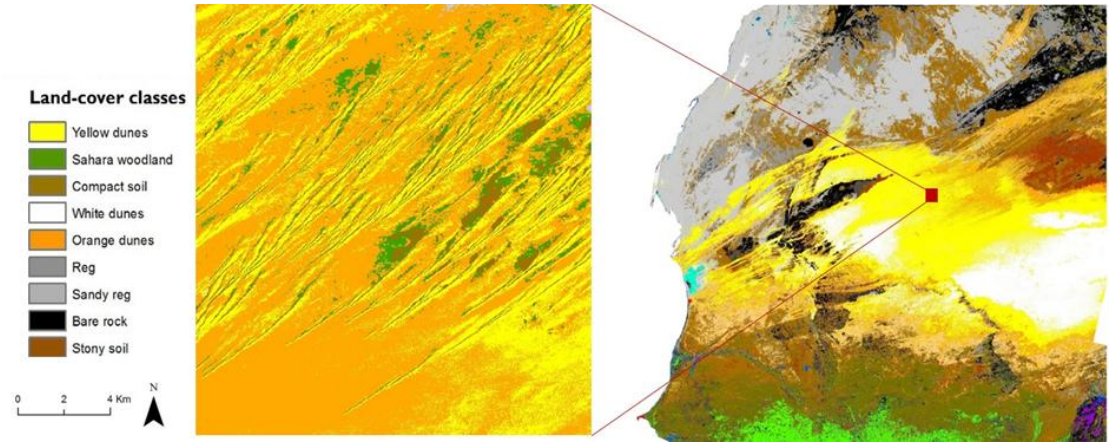

Fig. 5.5 - Remote inland area of Mauritania where a small and isolated group of *Addax nasomaculatus* has been suggested to persist. The finest zoom shows details of the fixed sands and flatter areas within and between dune fields that support perennial vegetation, representing similar habitat characteristics to the Nigerian areas where addax populations currently endure.

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Crocodylus suchus, *El Khedia, Mauritania (top)*

Photo: DV Gonçalves

Senegal River (bottom)

Photo: JC Campos

CHAPTER VI

Distribution and population connectivity of West African crocodiles in the West Sahara-Sahel

All things dull and ugly,

All creatures short and squat,

All things rude and nasty,

The Lord God made the lot.

Each little snake that poisons,

Each little wasp that stings,

He made their brutish venom.

He made their horrid wings.

Monty Python, Monty Python's Contractual Obligation Album (1980)

Article IV - Update of distribution, habitats, population size, and threat factors for the West African Crocodile in Mauritania*

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ABSTRACT

The West African Crocodile (*Crocodylus suchus*) is an emblematic species from the Sahara-Sahel with scarce knowledge on distribution and conservation status. This study updated the knowledge on distribution, occupied habitats, population size, and factors that threaten *C. suchus* and its habitats in Mauritania. Five field expeditions to Mauritania (2011-2016), allowed the detection of 26 new localities, increasing by 27% the current number of all known locations (adding up to N=96). In most localities less than five individuals were observed, and in all visiting sites the number of observed individuals ranged from one to 23. Eleven threat factors were identified, being droughts and temperature extremes (100% localities affected) and water extraction for domestic use and nomadic grazing (94%) the most frequent. These findings suggest that crocodiles are apparently vulnerable in Mauritania and that future local conservation strategies are needed to assure the continuity of its fragile populations and preserve their habitats.

Keywords: Aquatic habitats; Conservation; Crocodile distribution; *C. suchus*; Sahara; Sahel; Threat risk.

INTRODUCTION

The West African crocodile (*Crocodylus suchus*) is an emblematic species that was widely distributed across the Sahara until the early 20th century (Brito el al. 2011a). Increased aridity since the Mid-Holocene (around 7,000 years ago) combined with human persecutions led to local extinctions and the consequent range contraction and fragmentation (Brito et al. 2011a). Currently, *C. suchus* is distributed mostly across West Africa, from the north and west limits in Mauritania and Senegal, to the south and east limits in the Democratic Republic of the Congo and Uganda, respectively (Hekkala et al. 2011).

In Mauritania, the most comprehensive survey of crocodile populations assembled information for 78 localities, including 60 of confirmed presence, 10 of possible presence, five of unconfirmed status, and three of confirmed extinction (Brito et al. 2011a). New habitats and locations for crocodiles were discovered during that survey, but information remains incomplete for south-eastern Mauritania, particularly in the Afollé Mountain (see **Fig. 6.1**). Several threats affecting crocodiles were previously identified, namely overexploitation by herdsmen, faecal contamination by domestic animals and water abstraction for domestic uses (see Tellería et al. 2008; Brito et al. 2011a), but the identified threats were coarsely scrutinised. Recently, Vale, Pimm and Brito (2015) conducted a quantitative assessment of threats associated to gueltas (mountain rock pools), but other important aquatic habitats (e.g., rivers and lowland floodplains) in Mauritania where the species exists remain unevaluated in terms of extinction risk factors. A quantitative assessment of the factors affecting crocodile populations and its habitats in Mauritania is still unavailable. Given that *C. suchus* is currently categorised as Not Evaluated by IUCN (IUCN 2016), acquiring detailed information about its distribution, population status, and threat factors is crucial for updating its conservation status and to optimise future conservation planning.

Field expeditions to Mauritania since 2011 allowed the detection of new localities and the collection of further data on their threat risks. As such, this study: 1) updates the current distribution of *C. suchus* in Mauritania; 2) updates the knowledge about the habitats currently occupied by crocodiles; 3) updates estimates of crocodile population size at specific localities; and 4) quantifies the major threats for crocodile populations and the habitats in which they persist.

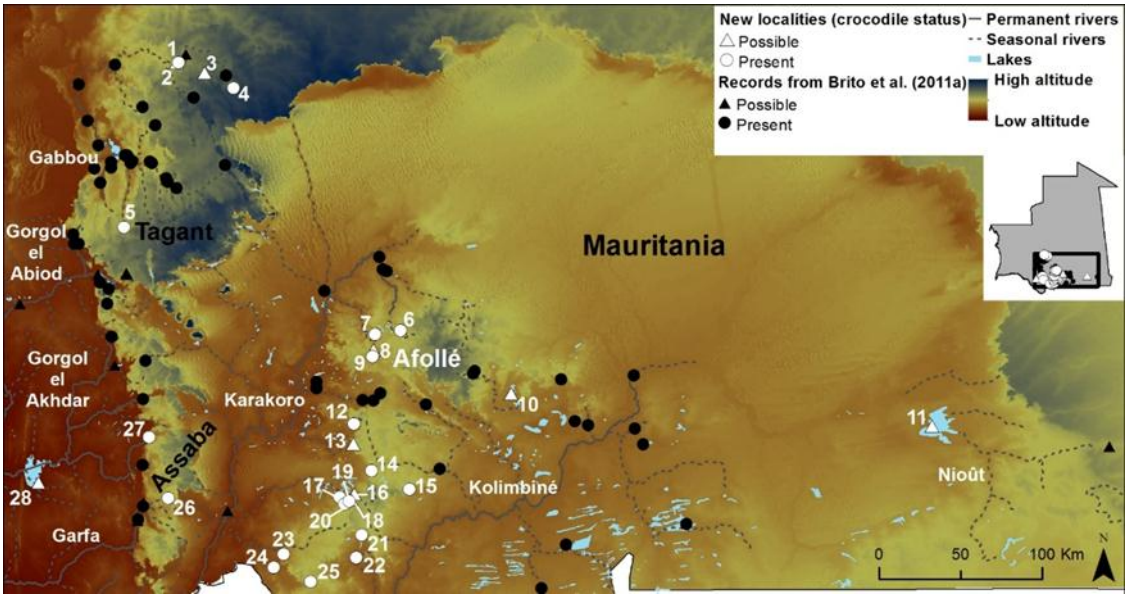

Fig. 6.1 - Study area and distribution data for *C. suchus*. New localities presented in this study (coded from 1 to 26) and previously published localities in which the crocodile status was updated (coded from 27 to 28) are represented in white triangles (possible presence of crocodiles) and in white circles (presence of crocodiles). Localities published in Brito et al. (2011a) are represented in black triangles (possible presence of crocodiles) and in black circles (presence of crocodiles). The names of the major mountains (black) and sub-basins (white) of the study area are written in bold.

METHODS

The study area encompasses the southern Mauritanian mountains of Tagant, Assaba and Afollé (**Fig. 6.1**). Five field expeditions were developed between 2011 and 2016, during the periods after the rainy season (October to December in 2011, 2012 and 2014; January to February in 2014 and 2016), totalling 58 sampling days. A total of 52 localities (of which 10 were visited in two or more occasions) were sampled for the presence of crocodiles by at least 4 persons, with a total sampling effort of 1.363 man/hours and an average of 0.273 man/hours per locality. Crocodile sampling followed the procedures described in Brito et al. (2011a): 1) visual inspection of water from elevated points using binoculars; 2) search of crocodile marks in shorelines, including faeces, footprints, tracks or excavated burrows; 3) inspection of rock crevices for hidden crocodiles; 4) sampling of water and margins at night with lamps; and 5) inquiries to locals about the presence of crocodiles. The number of crocodiles present at each locality was quantified. Inquiries to local people were conducted for acquiring information concerning the annual water availability of the location (permanent or seasonal) and the period when the locality dries. The coordinates of sampled localities

were gathered from a Global Positioning System (GPS). Localities were displayed in ArcGIS 10.1 on the WGS84 datum. Locality names used in this study are in accordance with the toponomies established in the topographic maps (1:200,000) from the French Institut Géographique National (IGN).

The status of crocodile populations at each locality was categorised as: 1) present, when crocodiles were observed during field expeditions or when faeces, footprints or burrows were found; and 2) possible, when locals reported the presence of crocodiles in apparently suitable habitats but no individuals or signs were observed. The type and number of threats associated to each locality were listed based on field assessments (**Table D.1 in Appendix D**). Threat types followed the nomenclature of IUCN Threats Classification Scheme (Version 3.2; http://www.iucnredlist.org/technical-documents/classification-schemes/threats-classification-scheme). Chi-Square independency tests were performed in R 3.1.1 (*stats* package) to verify if the total number of threats affecting each locality was differently related with the type of habitat, mountain, or hydrographic sub-basin. A distance matrix was constructed in R (*stats*) based on the presence/absence of the threats in each locality. The matrix was used to perform a Multidimensional Scaling analyses (MDS) in R (*MASS* package) to verify if the localities affected by different type of threats were grouped according to habitats, mountains, or hydrographic sub-basins. Analyses were restricted to localities where population status was classified as “present” or “possible” and combined localities listed in Brito et al. (2011a) and this work (**Table D.1 in Appendix D**). Localities listed in Brito et al. (2011a) where crocodile status was defined based only on bibliography or local inquiries were excluded, since the locality was not visited.

RESULTS AND DISCUSSION

The field expeditions allowed the identification of 26 localities where the presence of crocodiles was confirmed for the first time (**Fig. 6.1; Table D.2 in Appendix D**). In these localities, population status was categorised as present and possibly present in 17 and nine localities, respectively. These findings increased by 27% the total number of previously known localities of presence and possible presence in Mauritania (n=70), which now add up to 96 localities. The intensified sampling of the Afollé Mountain resulted in 14 new presence localities (82% of the new presence localities) and five localities where crocodiles were possibly present (56% of the new possible locations).

The acquired information for the Afollé (total of 19 new localities) increased by 59% the number of known localities in this mountain. Although the cryptic behaviour of crocodiles may constrain their detectability (Brito et al. 2011a), the considerable increase of crocodile localities probably reflects the lack of sampling in the region. Future fieldwork should be focused in the Kolimbiné and Nioût hydrographic basins, where sampling efforts will probably allow discovering additional crocodile populations. However, the remoteness and the harsh conditions that characterise southern Mauritanian mountains, as well as the insecurity caused by the current regional conflicts (Larémont 2011) constitute logistical challenges for local biodiversity surveys (Brito et al. 2014).

The field expeditions also allowed revising crocodile status in two localities (**Fig. 6.1; Table D.2 in Appendix D**). In Guelta Galoula (Locality 27), crocodiles were considered to be possibly present in Brito et al. (2011a), according to positive reports in the 1950s (Quézel 1978) and 1970s (de Smet 1999). The locality was visited during 2012 and the presence of crocodiles was confirmed based on direct observations of individuals and collection of faecal samples. In M'bout lake (Locality 28), crocodiles were considered to be possibly present by Brito et al. (2011a), according to positive reports in the 1930s (Joleaud 1933). The status was later changed to present (Brito et al. 2011b) since a skin sample was collected from a specimen allegedly captured in the locality by local people during 2008. However, the inconsistent results concerning the geographic origin of the sample provided by genetic data prevented the confirmation of crocodile presence (see Velo-Antón et al. 2014). As such, population status is here re-established as possible.

Of the 26 new localities where crocodiles were found to be present and possibly present, 14 were located in oueds (rivers), six in gueltas (mountain rock pools), three in tâmoûrts (seasonal floodplains at the foothills of mountains) and three in other habitats (**Table D.1 in Appendix D**). Overall, gueltas and tâmoûrts still represent the most used habitats by crocodiles in Mauritania (Brito et al. 2011a), accounting with 36% and 23% of the total known crocodile localities (N=96), respectively. In fact, due to the associated suitable climatic conditions and longer periods of water availability, these habitats act as refugia for the persistence of crocodiles and other vertebrate species in the mountains of Mauritania (Trape 2009; Vale, Pimm and Brito 2015). Oueds also stand as important habitats for crocodiles, representing 22% of the total known crocodile localities. The seasonal lagoons that are formed within the riverbeds may sustain populations for a limited period of time after the rainy season. During the dry season crocodiles may find shelter between rock boulders or in excavated burrows in

the muddy margins. Oueds are apparently crucial for crocodile dispersal between the mountain gueltas and the lowland tâmoûrts, and molecular data suggested that patterns of population structure are dependent on the geographical connectivity of hydrographic sub-basins (Velo-Antón et al. 2014).

A total of 56 crocodiles were counted in 11 of the new and updated locations (**Table D.2 in Appendix D**). The majority of individuals was observed in the southern Afollé Mountains, where 39 individuals were counted among four localities (Localities 17, 20, 21, 23). The southern regions of Mauritania are characterised by greater water availability and water flow (Campos, Sillero and Brito 2012), which translates in wider availability of suitable habitats that might be able to sustain larger crocodile populations. In the remaining localities (N=7), less than five individuals were counted, which corresponds to the pattern of general low population size previously reported for Mauritania (Brito et al. 2011a).

The analyses of threats for the localities listed in Brito et al. (2011a) and in this study (N=85 localities) identified 11 threat factors that can directly affect crocodile populations and their habitats (**Table 6.1**). Severe droughts and temperature extremes affected all localities while water extraction for domestic use and nomadic grazing were also very common, which is in agreement with previous assessments focused on gueltas only (Vale, Pimm and Brito 2015). The frequent climatic fluctuations and the consequent oscillations in inter-annual water availability characterise the arid and semi-arid regions of the Sahara-Sahel (Haas et al. 2009; Campos, Sillero and Brito 2012). These regions are normally exposed to severe droughts and humid habitats become crucial for sustaining the local biodiversity as well as local human populations (Brito et al. 2014). Humid habitats are intensively explored by humans for domestic (e.g., abstraction of water for human and cattle consumption) and agricultural use, which can lead to other worrisome threats, such as excessive faecal contamination and water eutrophication (Tellería et al. 2008; Brito et al. 2011a). The Chi-Square tests revealed that the considered localities are threatened independently of the type of habitat ($p=0.03$), mountain ($p=0.1$) or sub-basin ($p=0.03$). The MDS analyses showed that localities affected by different type of threats were not grouped according to habitats, mountains, or hydrographic sub-basins (see example in **Fig. D.1 in Appendix D**). These results indicate that the different humid habitats in which crocodile populations persist are similarly threatened and exploited by the local communities. Human activities (e.g., pastoralism) disturb crocodiles during daylight and over-exploitation of humid habitats may cause local shortage of water availability. Both factors affect physiological processes of crocodiles (e.g., feeding, growth and reproductive periods)

and further restrain the already limited annual active period of crocodiles (Brito et al. 2011a). Studies focused in the ecology and physiology of local crocodile populations are needed to evaluate possible stresses induced by the current habitat disturbances.

West African crocodiles are currently categorised as Not Evaluated by IUCN (IUCN 2016). The threats identified in this study provide baseline data for the future assessment of *C. suchus* conservation status at both global and regional level (in Mauritania). Current predictions of climate change suggest precipitation decreases and a continuous warming in Africa, principally in flat desert environments (Loarie et al. 2009). Therefore, global warming represents a major threat for local crocodile populations and for other water-dependent species that share the same habitats (Vale, Pimm and Brito 2015). Conservation strategies promoting the protection of water bodies and also their sustainable management and use by the local communities are needed, to assure the continuity of crocodile populations in the fragile, scarce and mostly seasonal humid habitats in which they persist.

Table 6.1 - Threat code, threat definition and number and percentage of crocodile localities affected by each threat (according to the IUCN Threat Classification Scheme).

Code	Threats	N of localities (%)
2.1.2	Small-holder farming	23 (27)
2.3.1	Nomadic grazing	80 (94)
2.3.2	Small-holder grazing, ranching or farming	47 (55)
7.2.1	Abstraction of surface water (domestic use)	80 (94)
7.2.3	Abstraction of surface water (agricultural use)	38 (45)
9.1.3	Pollution: Type Unknown/Unrecorded (faecal contamination)[1]	24 (28)
9.1.3	Pollution: Type Unknown/Unrecorded (detergents)[2]	10 (12)
9.3.3	Pollution: Herbicides and pesticides	23 (27)
10.3	Avalanches/landslides	18 (21)
11.2	Droughts	85 (100)
11.3	Temperature extremes	85 (100)

1 Threat related with the faecal contamination of water by drinking cattle. The threat was classified as “Pollution: Type Unknown/Unrecorded” because it did not fit into any category of the IUCN Threat Classification Scheme.

2 Threat related with the contamination of water by detergents used for domestic washing. The threat was classified as “Pollution: Type Unknown/Unrecorded” because it did not fit into any category of the IUCN Threat Classification Scheme.

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Article V - Unexpected strong distance effects on dispersal and population connectivity of desert crocodiles

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ABSTRACT

Habitat connectivity is pivotal for desert aquatic species survival by allowing gene flow between its typically isolated populations. West African crocodiles occur in the Sahara-Sahel in relict and isolated populations, and in this work, we evaluate how water networks can affect connectivity and the dispersal dynamics of this species. We related genetic patterns of crocodiles with a contemporary water connectivity scenario (2010s) derived from remote sensing. We built a historical scenario representative of regional drought (1980's), for verifying how aridification can hamper connectivity in deserts. We found unexpected genetic isolation by distance in crocodiles, whose populations are grouped in different hydrographic basins. Dispersal distances are apparently mediated by water networks, which connect most of the water bodies during the rainy seasons. The limited water availability of the historical scenario exemplifies how droughts might severely impact connectivity in deserts. Aridification is driving ecological and evolutionary traits of desert species, whose survival might be compromised according to climate change predictions for desert environments.

INTRODUCTION

Deserts are generally characterized by harsh climatic conditions and scarcity of natural resources (Durant et al. 2012), major drivers of ecological and evolutionary processes of desert species (Wilson and Pitts 2012; Davis et al. 2013; Van Dam et al. 2016). Water-networks are critical in the survival of desert species, by providing sustenance conditions and dispersal opportunities (Davis et al. 2017a). Temporary streams are the main dispersal route for aquatic organisms, usually limited to isolated water-bodies in which they persist (Murphy et al. 2012; Murphy et al. 2015). The continuous isolation of desert species might lead to their extinction through eventual inbreeding and demographic processes (Frankham et al. 2005). By allowing dispersal movements between water bodies, water networks are essential to maintain gene flow and population connectivity that might secure the long-term persistence of desert species (James et al. 2017).

In general, the potential effects of spatial and temporal dynamics of water connectivity and population dynamics under climate change scenarios are poorly known (Jaeger et al. 2014). This knowledge is even scarcer in deserts, whose drought periods or long-term increases in aridification should greatly impact water connectivity, and ultimately, gene flow levels and population structure (Pilger et al. 2015). Aridification and droughts might cause the disappearance of water networks and connectivity, which consequently disrupt potential meta-population dynamics, and lead to the permanent isolation of desert populations and their successive extinction (Turner et al. 2015).

Desert populations of the West African crocodile (*Crocodylus suchus*) within the Sahara-Sahel constitute a good model to evaluate the potential impacts of aridification in population structure and connectivity. In Mauritania, crocodiles occur in about 100 isolated populations and inhabit water-bodies scattered along multiple hydrographic basins (**Fig. 7.1**), which are temporarily linked by seasonal streams (Brito et al. 2011; Campos et al. 2012, 2016). The genetic structure identified in Mauritanian populations has been associated to local gene flow patterns within sub-basins, suggesting seasonal streams as dispersal routes (Velo-Antón et al. 2014), however the demographic dynamics underlying the connectivity between water bodies is unknown. As such, comparing the genetic patterns of crocodiles with the contemporary dynamics of water networks is crucial to understand how recent climatic changes might shape the connectivity of crocodile populations and other desert species.

Here we evaluate the role of aridification on the connectivity, genetic patterns and dispersal dynamics of *C. suchus* populations. We assumed that the genetic patterns of crocodiles reflect the current picture of dispersal dynamics and water connectivity. We used 12 microsatellite markers for measuring the genetic diversity, population structure and gene flow of crocodiles. We conducted Remote Sensing (RS) analyses to build water availability maps for a contemporary (2010s) period. We used the current water availability map in a landscape connectivity analysis for quantifying the contemporary water network connectedness. We used an integrative approach for testing isolation by resistance (IBR) scenarios, by correlating the genetic distances between crocodile individuals and the resistance distances between locations obtained from the RS-water connectivity maps, always assuming the isolation by distance (IBD) as null hypothesis. Finally, we built a RS-water map for a historical period of drought in the 1970s-80s and used it in a landscape connectivity analyses, to verify potential losses of water network connectedness caused by intensive aridification. The present study provides cues for setting conservation plans of aquatic desert biodiversity under scenarios of rapid and extreme climate change and aridification.

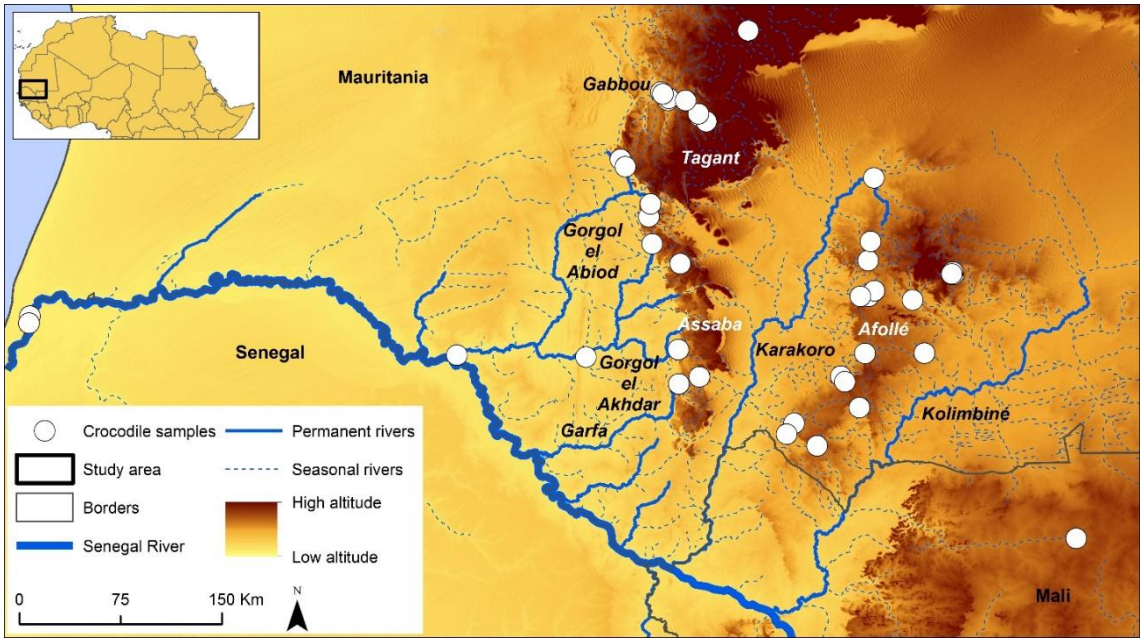

Fig. 7.1 - Study area and *Crocodylus suchus* samples (white circles) used in this study (n=139). The zoom displays the current study area with country names written in bold. Major mountains and hydrographic sub-basins are written in white and black italics, respectively.

METHODS

STUDY AREA AND SAMPLE COLLECTION

The study area encompasses an area of approximately 454,013 km2, varying between 18.5°N, 13.5°N, 16.5°W and 9°W, comprising southern Mauritania, south-western Mali and north-eastern Senegal (**Fig. 7.1**). Climate is characterized by a dry and cold season from November to February and a dry, hot season from March to June (Cooper et al. 2006). Variation in annual average temperature is relatively small (variation of 10ºC approximately) and tends to follow altitudinal gradients. Annual precipitation is scarce and seasonal, occurring in a single wet period from July to October (**Fig. E.1 in Appendix E**), with most of the rain falling in August and September (Cooper et al. 2006). The area is characterized by three major mountain reliefs in southern Mauritania, the Tagant, Assaba and Afollé (**Fig. 7.1**), which are associated with six important hydrographic sub-basins (Brito et al. 2011; Campos et al. 2016): 1) the endorheic and apparently isolated Gabbou within the Tagant; 2) the Gorgol el Abiod, that drains water from the southern Tagant and northern Assaba; 3) the Gorgol el Akhdar and 4) Garfa sub-basins, that are originated from water run-offs of the western Assaba; 5) the Karakoro, that flows between the Assaba and Afollé, although mostly fed by run-offs from the later mountain, and is characterized by low water availability; and 6) the Kolimbiné, that flows east-ward of the Afollé. With the exception of the Gabbou, the other five sub-basins flow to the Senegal River and are composed by mountain rock pools (locally known as *gueltas*) and seasonal floodplains (locally known as *tâmoûrts*).

A total of 139 samples of *C. suchus* were collected across 44 localities from fieldwork expeditions between 2007 and 2016. Samples were composed by 17 fresh tissues from animals captured in the field (tissues extracted from the tail tips using a scale-clip), seven near fresh tissues (from crocodiles found recently dead), four skin fragments from aged carcasses, seven bone remains (skulls and dorsal scales) and 104 fecal remains (**Table E.1 in Appendix E**). Crocodiles were captured by hand or by hand-nets, and tail tips (5 mm piece) were cut and stored in separate tubes with 96% ethanol for genetic analysis. Team members obtained the tissue samples following ethical guidelines for use of live reptiles (Velo-Antón et al. 2014). After sample collection, individuals were promptly released on capture site. Near fresh samples were kept in tubes with 96% ethanol, while skin fragments, bone remains and

fecal remains were collected in empty tubes or plastic bags. All the samples were manipulated using gloves for avoiding any source of contamination.

CONTEMPORARY AND HISTORICAL WATER AVAILABILITY/CONNECTIVITY

RS analyses were performed to quantify water availability in the study area during the contemporary (2010s) and historical periods (1970s-80s). For the contemporary water detection analysis, satellite images from Landsat 8 (30x30 m resolution) were extracted from the Global Visualization Viewer (GLOVIS; http://glovis.usgs.gov/) of the United States Geological Survey (USGS; **Table E.2 in Appendix E**). For the same Landsat quadrants, one image per year was extracted for the period between 2013 and 2016. Images were selected from periods during or immediately after the rainy season (July-November) (Cooper et al. 2006). These periods were chosen for maximizing the assessment of water availability in the region. Only images with less than 10% of cloud cover were used. All Landsat images were georeferenced by the United States Geological Survey (http://landsat.usgs.gov/) and the analyses were developed on the datum WGS-1984. Atmospheric corrections and haze-removal procedures were conducted for all extracted images using the calibration coefficients of the ATCOR tool of PCI Geomatica (Richter 1996, 2010). A mean image per Landsat quadrant for the humid periods of 2013-2016 was calculated using PCI Geomatica v. 2016 (http://www.pcigeomatics.com/#). For each mean quadrant, water bodies were identified using two normalized difference water indexes (NDWI), the Gao's NDWI (NDWI1; Gao et al. 1996) and the Xu's modified NDWI (MNDWI; Xu et al. 2006), which use arithmetic combinations of image spectral bands to enhance water from non-water pixels (see Campos et al. 2012 for details). The MNDWI and NDWI1 were selected given their good performances in the study area for identifying permanent and seasonal water, respectively (see Campos et al. 2012). Indexes were calculated according to Gao et al. (1996) and Xu et al. (2006) and the resulting images were mosaicked for the entire study area. Margin effects between overlapping scene regions were removed from the mosaics using the "OrthoEngine mosaicking tools" from PCI Geomatica. Water reclassification thresholds, following Campos et al. (2012), were defined using GPS-control points of water bodies obtained during field expeditions between 2011 and 2016. Three categories of water availability were recorded: non-water, seasonal water and permanent water. A total of 3000 control points were selected and posteriorly allocated in two datasets (**Table E.1 in Appendix E**): 80% for water threshold selection (n=2400) and 20% for threshold validation (n=600). Raw index values were reclassified into a water availability map (30x30 m) using the

resultant thresholds (MNDWI>0=permanent water and NDWI1>0=seasonal water; **Fig. E.2 in Appendix E**).

For the historical water detection analysis, satellite images from Landsat 4-5 Thematic Mapper (TM) were extracted from GLOVIS. Images were selected to cover the rainy seasons between 1984 and 1987. This time period was chosen for covering the dry conditions that endured in the Sahara-Sahel transition zone between the 1970s-80s (Hulme 2001; Foley et al. 2003; Frappart et al. 2009). Due to the frequent gaps of satellite data during the 1970s, the entire drought period was not covered. Still, the satellite temporal window obtained is representative of the epoch, since one of the year sequences with the most severe dry conditions was verified between 1983 and 1985 (see Frappart et al. 2009; **Fig. E.3 in Appendix E**). The satellite image treatment, processing and water identification followed the aforementioned methodological steps conducted for the contemporary analysis, with exception of the water threshold selection. Given the unavailability of water control points for the 1980's, we assumed the same water thresholds previously demarcated in the contemporary analysis (**Fig. E.2 in Appendix E**). All RS analyses were performed in PCI Geomatica, while the threshold selection and water reclassification procedures were processed in ArcGIS 10.1 (ESRI 2012). Finally, a spatial correlation analysis was performed using the "Band Collection Statistics" in ArcGIS to verify if the historical and contemporary water availability maps were statistically different.

CONNECTIVITY OF C.SUCHUS *POPULATIONS*

Landscape connectivity analyses were conducted to verify potential connections among crocodile sites across the study area and to test possible hypotheses of IBD and IBR. The IBD (i.e. Euclidean distance between crocodile sites) was considered as the null hypothesis, while IBR was tested based on landscape scenarios built using water availability as a potentially influential variable for crocodile dispersal, due to the indisputable water dependency of crocodiles to survive and to disperse (Brito et al. 2011; Campos et al. 2016). Landscape resistance surfaces were generated based on the obtained water availability maps (see above). Two principal scenarios of landscape resistance were built (see **Table E.3 and Fig. E.4 in Appendix E** for details): 1) "water" scenario, in which both permanent and seasonal water were considered as equally important to crocodile dispersal (same resistance values); 2) "water seasonality", in which permanent water was considered more important for dispersal than seasonal water (permanent water resistance<seasonal water resistance). The resistance

scenarios were implemented in a landscape connectivity analysis using CIRCUITSCAPE 4.0.5 (Shah and McRae 2008). The “water seasonality” scenario for the past was chosen for analyzing the historical connectivity, using the current water locations as connectivity nodes. All resistance surfaces were resampled to a spatial resolution of 150 m and the area was divided into tiles following the procedures in Pelletier et al. (2014), in order to optimize the software processing performance. Cumulative current maps indicating potential corridors for crocodiles and pairwise distances of cumulative resistance between all crocodile site pairs over all possible pathways were obtained. Finally, a spatial correlation analysis was performed using the “Band Collection Statistics” in ArcGIS to verify if the historical and contemporary connectivity maps were statistically different.

DNA EXTRACTION AND GENOTYPING

The DNA extractions for fresh and near fresh samples were conducted using the EasySpin Genomic DNA Tissue Kit or the QIAamp DNA Micro Kit (QIAGEN). DNA extractions of fecal remains were performed through a preliminary GuSCN/silica method Boom et al. (1990), followed by the extraction protocol of Frantz et al. (2003). The QIAamp DNA Micro Kit (QIAGEN) was used for DNA extraction of skins and bone remains. All the pre-PCR procedures of non-invasive samples were led in a dedicated laboratory used only for the manipulation of low quality DNA under sterile conditions and quantified DNA through fluorimetry, excluding samples with a DNA concentration lower than 0.4 mg/ml.

A set of 12 nuclear microsatellite loci previously developed for *Crocodylus* (FitzSimmons et al. 2001; Miles et al. 2009) were used for genotyping in multiplex reactions. This set of microsatellites was successfully used for invasive and non-invasive *C. suchus* samples in a preceding work (Velo-Antón et al. 2014), revealing to be highly informative for *C. suchus* genetic variability. PCR amplification was performed using the Multiplex PCR Kit (QIAGEN) following manufacturer’s instructions in a final 10-µl volume comprising 5ul of Master Mix, 1µM of mix containing forward, reverse and tail primers and approximately 10 ng of DNA. The M13-primer fluorescent labeling protocol (Schuelke 2000) was used with four different dye-labeled tails and forward primer concentration of 1/10 of reverse and tail primers. PCRs were carried out on a BIORAD T100 and were performed twice and at least four times for high quality and low quality DNA, respectively. For details concerning the markers, primers, allele range and PCR conditions of each multiplex reaction, see the published data in Velo-

Antón et al. (2014). PCR products were separated by size on an ABI3100xl Genetic Analyser. Allele sizes were scored against the GeneScan-400 LIZ Size Standard, using the GENEMAPPER 4.0 (Applied Biosystems) and manually checked.

GENETIC DIVERSITY AND POPULATION STRUCTURE OF C. SUCHUS

Significant deviations from Hardy-Weinberg equilibrium and linkage disequilibrium between the six genetic demes identified (see structure analyses below) were tested using ARLEQUIN 3.5.1.3 (Excoffier and Lischer 2010). The significance tests were performed through a Markov chain method with 1,000 dememorization steps, 10,000 permutations and sequential Bonferroni correction (Rice 1989). Indices of genetic diversity, namely number of alleles per locus (NA), observed (Ho) and expected (He) heterozygosities, and inbreeding coefficient (FIS), were calculated through ARLEQUIN, using the 12 loci dataset for each genetic group. The number of private alleles (Np) and the Queller and Goodnight (1989) statistic rxy to calculate pairwise relatedness between individuals were estimated using GenAlEx 6.5 (Peakall and Smouse 2012). Allelic richness (AR) was estimated through FSTAT 2.9.3 (Goudet 2001). Pairwise Fst values (Weir and Cockerham 1984) were calculated in ARLEQUIN, in order to estimate genetic differentiation among genetic groups identified in the structure analysis. Significance of pairwise comparisons were inferred by an exact test with 1,000 iterations, adjusting p-values with the sequential Bonferroni correction.

Population structure was evaluated through a Bayesian clustering method implemented in STRUCTURE 2.3.4 (Pritchard et al. 2000). The analyses were performed using 10 runs per K-value (number of genetic demes) ranging from 1 to 10, a burn-in period of 1,000,000 and a run length of 5,000,000 iterations. The analyses were run based on an admixture model with uncorrelated allele frequencies and without prior information on sample population membership. The most likely K-value was estimated by Structure Harvester 0.6.94 (Earl and vonHoldt 2012) through the Delta K (Evanno et al. 2005) and ln Pr(X|K) Probability of K (Pritchard et al. 2000) methods.

GENETIC DIVERSITY AND POPULATION STRUCTURE OF C. SUCHUS

Genetic distances among crocodile individuals were calculated through PCA-based metrics in the R statistical environment (R Core Team 2016), following the procedures of Shirk et al. (2010, 2017). All the PC axes were used to calculate the final genetic distances. The Euclidean distances amongst crocodile locations were calculated using

the “ecodist” package implemented in the R software. Finally, Mantel tests (Smouse et al. 1986) and partial-Mantel tests (partial-Mantel tests using the Euclidean distance as correcting variable) were applied for assessing the correlation between pairwise estimates of genetic distances (from PCA-based metrics) with the pairwise Euclidean distances amongst crocodile sites and with the pairwise cumulative resistance distances from each landscape resistance scenario (from the CIRCUITSCAPE analyses). Mantel and partial-Mantel tests were performed using the “vegan” package implemented in the R software (R Core Team 2016). Mantel’s r scores were compared to evaluate if the resistance distances (IBR) were more correlated with the genetic distances than the Euclidean distances (null hypothesis of IBD).

RESULTS

CONTEMPORARY AND HISTORICAL WATER AVAILABILITY/CONNECTIVITY

The RS analyses showed clear differences in water availability for the contemporary and historical periods (correlation score of 0.01), detecting high water availability in the contemporary period (**Fig. E.5 in Appendix E**). The two water indexes (WIs) were capable of identifying permanent and seasonal water with high accuracy (validation results in **Table E.4 in Appendix E**), yielding a detailed water availability map for the region (**Fig. E.5 in Appendix E**). The derived water map indicated that the study area is characterized by high water availability in the south, in which sub-basins can interconnect through seasonal courses. Expectedly, the Senegal River constitutes the major hydrographic feature in the region, engulfing most of the water that flows across secondary sub-basins. On the contrary, in northern areas there is less water available, though most of the permanent aquatic habitats are connected by seasonal streams both within and between main sub-basins. The WIs calculated for the historical period show considerable lower water availability in comparison to the current epoch (**Fig. E.5 in Appendix E**). During this dry period, most sub-basins were permanently dry and spatially undistinguishable, and the Senegal River was reduced to a narrow and discontinuous course.

CONNECTIVITY OF C. SUCHUS *POPULATIONS*

The estimates of contemporary and historical water availability were manifestly crucial for depicting the landscape connectivity patterns for *C. suchus* populations (**Fig. 7.2**). The circuit analysis attributed high current values to the major watercourses under the best explanatory contemporary landscape scenario ("water seasonality"; see above), depicting the regional streams as potential dispersal routes for crocodiles. These were observed within and between each hydrographic sub-basin, in which permanent streams were identified as the connections with the highest probabilities of passage (high cumulative current). With exception of the Gabbou and the northern Karakoro, all sub-basins were composed by dispersal paths that flow into the Senegal River. The Senegal River is indicated as the largest corridor, potentially acting as the main dispersal route for crocodiles distributed across the region. Circuit analysis performed for the historical period (see above) show a statistically different pattern in relation to the contemporary period (correlation score of 0.13), presenting a considerable reduction of landscape connectivity (**Fig. 7.2**). The vast majority of crocodile sites were surrounded by gradual and isotropic current values across the region, a pattern of isolation derived from the absence of connectivity pathways. The Senegal River was depicted as the major dispersal corridor, although condensed into a contracted and discontinuous path. Comparing both periods (**Fig. 7.2**), the connectivity losses during the historical drought period in the 1980's were mostly located in northern areas.

GENETIC DIVERSITY AND POPULATION STRUCTURE OF C. SUCHUS

Only one locus deviated from Hardy-Weinberg equilibrium (CpP1409; $P<0.05$ after Bonferroni correction) at Gorgol el Abiod/Southern basins and Karakoro adult groups. Since this deviation occurred only at two groups for the adults and was not observed for the juveniles' dataset, all loci were retained in the analyses. No evidence of linkage disequilibrium was found between any pair of loci. The 12 microsatellite loci dataset presented low to moderate levels of polymorphism, in which the number of alleles per locus varied between two and twelve. Overall, the results indicate low values of genetic diversity for the Western African crocodiles (**Table 7.1**). The highest genetic diversity was measured in the crocodiles from the southern basin of Kolimbiné, displaying the highest averages of number of alleles (Na=6.75), allelic richness (AR=2.67), observed heterozygosity (Ho=0.65) and expected heterozygosity (He=0.71). The lowest genetic diversity was observed in crocodiles from the endorheic

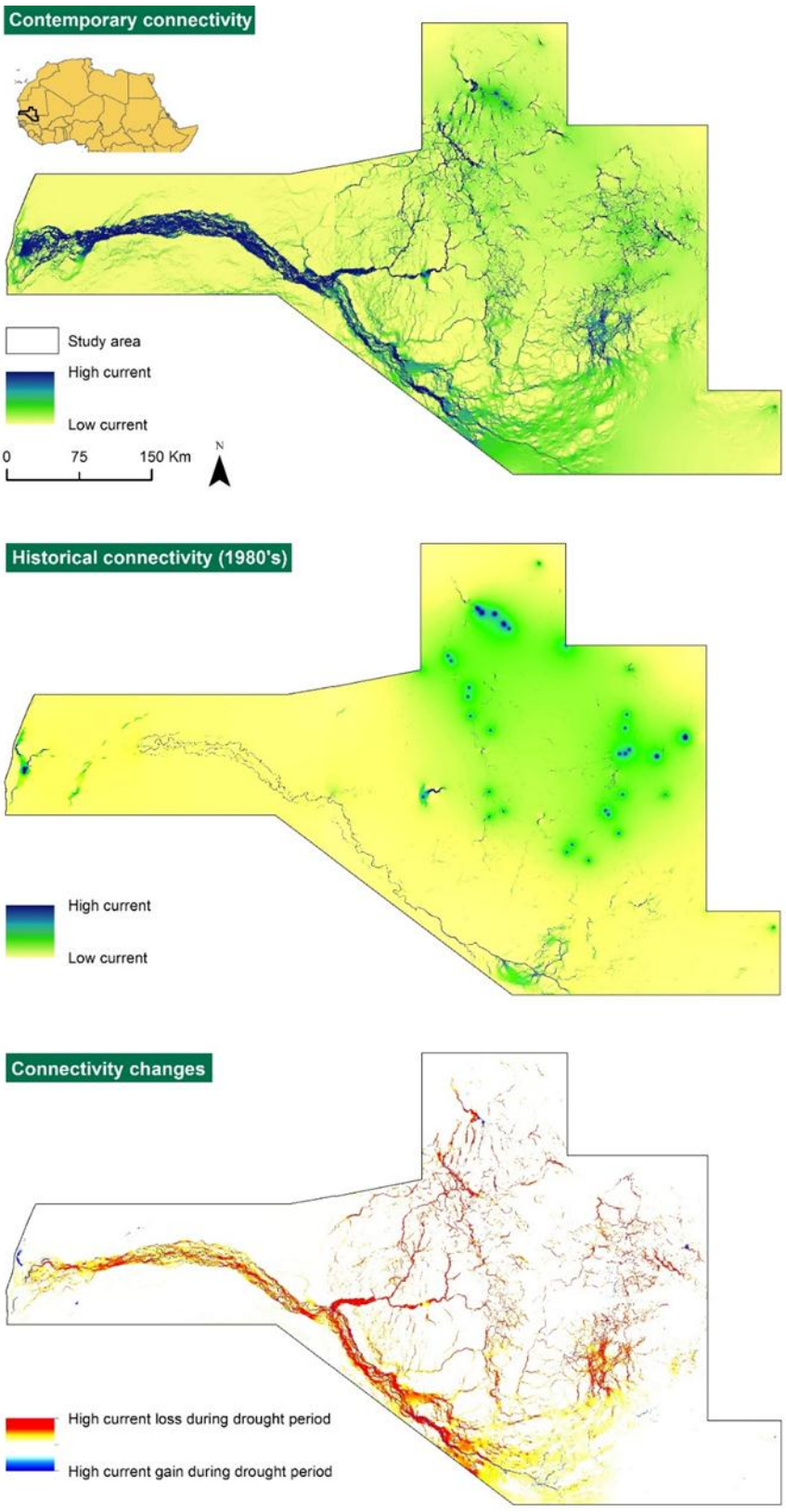

Fig. 7.2 - Contemporary connectivity (top), historical connectivity (middle) and connectivity changes (bottom) of *Crocodylus suchus* populations. The contemporary connectivity is based on the best contemporary landscape scenario ("Water seasonality"). Historical connectivity is based on the same landscape scenario, but derived for the 1980's. High cumulative current is represented in blue for both maps, showing the highest connectivity among crocodile sites. The connectivity change map represents the connectivity that was lost during a historical drought period in the 1980's (highest current loss symbolized in red), in relation to the contemporary connectivity scenario.

sub-basin of Gabbou, comprising the overall minimum values for all genetic diversity measures. The results showed general low levels of inbreeding, according to the inbreeding coefficient (FIS) and pairwise relatedness (rxy) values.

The STRUCTURE analyses identified genetic structure within the overall dataset (**Fig. 7.3**). The Delta K and the ln Pr(X|K) Probability of K identified six genetic groups (K=6) as the most probable structure level (**Fig. E.6 in Appendix E**). The grouping of crocodiles into populations was apparently related with the hydrographic sub-basins spatial structure (e.g. Gabbou, Gorgol el Abiod, Karakoro and Koungo). The groups of the Senegal River and Kolimbiné appear to be subjected to higher levels of gene flow, in comparison to the other genetic groups. In fact, while the Senegal River group comprises individuals from some of the southern sub-basins (e.g. Gorgol el Akhdar), the southern individuals of the Kolimbiné are grouped in the geographically proximate sub-basin of the Karakoro.

Pairwise Fst values (**Table 7.1**) retrieved a high and significant genetic differentiation between the Gabbou and the remaining sub-basin populations (mean pairwise Fst of 0.23), varying between 0.16 (between the Gabbou and the geographically proximate Gorgol el Abiod group) and 0.33 (between the Gabbou and the extreme southern group of Koungo, Mali). Contrarily, the population of the Kolimbiné sub-basin was associated with low to moderate genetic differentiation levels between all the remaining groups (mean pairwise Fst of 0.13), ranging from 0.10 (between the geographically proximate southern sub-basins of the Karakoro and the Koungo) and 0.22 (between the apparently more isolated Gabbou group).

Table 7.1 - Genetic diversity measures in *Crocodylus suchus* from Mauritania/Mali on six genetic groups (standard deviation in brackets). The number of genotyped individuals (N), mean number of alleles per locus (Na), number of private alleles (Np), allelic richness (AR), observed heterozygosity (Ho), expected heterozygosity (He), inbreeding coefficient (FIS) and pairwise relatedness (rxy) for each group are indicated. The triangular matrix indicates pairwise genetic distance (Slatkin's linearized Fst) among groups.

Populations	N	Na	Np	AR	Ho	He	F_{IS}	r_{xy}	Gabbou	Senegal River	Karakoro	Koungo	Kolimbiné	Gorgol el Abiod
Gabbou	22	4.25 (1.23)	2	2.16 (0.39)	0.50 (0.17)	0.55 (0.15)	0.06	-0.06 (0.30)	-	0.25	0.20	0.33	0.22	0.16
Senegal River	13	4.42 (1.61)	5	2.44 (0.61)	0.55 (0.25)	0.62 (0.22)	0.12	-0.10 (0.31)	-	-	0.23	0.26	0.11	0.18
Karakoro	47	5.58 (2.53)	3	2.35 (0.61)	0.55 (0.20)	0.59 (0.22)	0.02	-0.02 (0.24)	-	-	-	0.17	0.10	0.17
Koungo	14	4.92 (1.50)	6	2.48 (0.59)	0.59 (0.23)	0.67 (0.12)	0.01	-0.12 (0.29)	-	-	-	-	0.10	0.21
Kolimbiné	27	6.75 (2.71)	4	2.67 (0.41)	0.65 (0.12)	0.71 (0.11)	0.09	-0.04 (0.19)	-	-	-	-	-	0.11
Gorgol el Abiod	16	5.17 (1.72)	4	2.57 (0.44)	0.60 (0.11)	0.68 (014)	0.09	-0.07 (0.27)	-	-	-	-	-	-
Mean	23.2	5.18	4	2.45	0.57	0.64	0.07	-0.07						

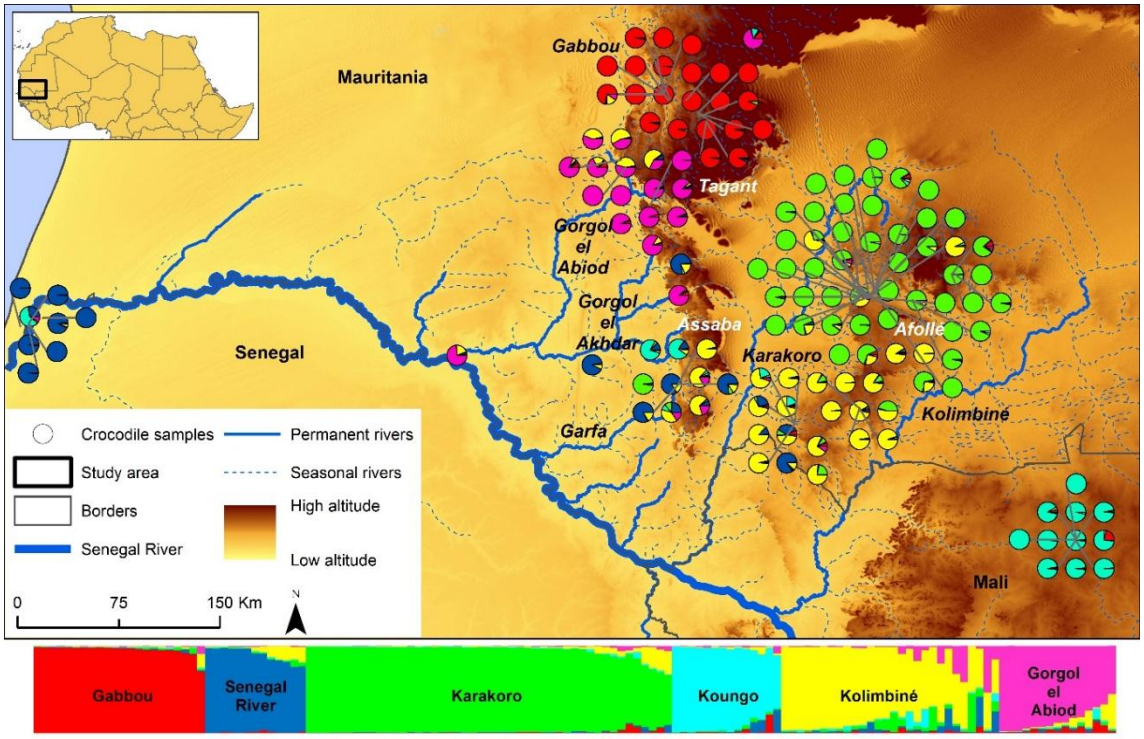

Fig. 7.3 - Population structure of *Crocodylus suchus*. The most likely K-value is shown (K=6). Genetic groups are represented in different colors across the study area, matching the color display of the structure plot. Bar colors of the plot depicts the probability of cluster assignment of each individual. The genetic deme names are indicated in the structure plot, while the sample codes are presented below the plot.

Genetic connectivity of C. suchus

Euclidean distances were more correlated with PCA-genetic distances between *C. suchus* individuals (R=0.47) than the landscape resistance scenarios (R=0.04 and R=0.08 for the “water” and ”water seasonality” scenarios, respectively). For these reasons, isolation by resistance (IBR) was rejected in favor of isolation by distance (IBD). current epoch (**Fig. E.4 in Appendix E**). During this dry period, most sub-basins were permanently dry and spatially undistinguishable, and the Senegal River was reduced to a narrow and discontinuous course.

Discussion

Overall, our results indicate a strong relationship between the geographic distance and the genetic patterns of *C. suchus*, supporting the null hypothesis of IBD. Although

unexpected, the IBD hypothesis might be explained by the particular dynamics of water networks in deserts. During the driest periods of the year (**Fig. E.1 in Appendix E**), water connectivity reaches its minimum level, which ultimately increase the effects of IBD. However, during the rainy seasons, seasonal water becomes extraordinary abundant, connecting the majority of the water bodies across desert regions. Given that the water networks are continuous and the seasonal water is vastly distributed across the region, crocodile dispersal might not closely follow stream flows, but rather seasonal water boundaries. For these reasons, the distance effect continues to prevail. Other studies have found this pattern in aquatic desert species (e.g. Phillipsen et al. 2015). As strict aquatic species, crocodiles are highly sensible to changes in water availability, which are likely to induce oscillations in landscape connectivity and ultimately in population structure. The climatic oscillations in the Sahara-Sahel induced cycles of wetter and dryer conditions that affected the spatial-temporal variability in water availability (Drake et al. 2011), which in turn might influence population connectivity. The connectivity among crocodile populations might be enhanced by the estimated contemporary increase in water availability (also impacting on increasing local population size; see **Fig. E.7 in Appendix E**), which might be considerably high during the wetter periods.

Extreme desert environments test the adaptive plasticity of aquatic organisms to endure under harsh and variable conditions. While the arid conditions of deserts generally cause population isolation in water-dependent species (Davis et al. 2017b), high dispersal capabilities may allow species to avail from infrequent and short-time opportunities for migration, restoring gene flow rates and counteracting the effects of population isolation (Murphy et al. 2015; James et al. 2017). The spatial and temporal constraints associated to water corridors (generally narrow and unpredictable in duration) might decrease the rate of dispersal success, possibly persuading crocodiles to remain in water-bodies.

The levels of genetic diversity and population sub structuring point towards genetic isolation and metapopulation dynamics of *C. suchus* in the small and scattered Mauritanian water-bodies, as observed at local and regional scales (Velo-Antón et al. 2014; Cunningham et al. 2016). The mountain biodiversity hotspots can act as refugia for crocodile populations and other water-dependent species (Trape 2009), which in turn may function as source of individuals for downstream populations (Brito et al. 2011; Campos et al. 2016). This source-sink dynamic is corroborated by the disproportional genetic admixture hanging towards most of the regional southern basins. These habitats are particularly exposed to severe droughts and temperature

extremes (Vale et al. 2015; Campos et al. 2016). Climate change projections propose possible precipitation declines and gradual warming in flat desert environments (Loarie et al. 2009), particularly in the Sahara-Sahel (Held et al. 2005; Giannini 2015), a scenario that may lead to the disappearance of aquatic biodiversity hotspots and associated water connections (e.g. Jaeger et al. 2014; Pilliod et al. 2015). Future aridification may subject crocodile populations to increased isolation and consequent extinction risks due to stochastic events and genetic drift, as it was shown here for the historical dry period in the 1980s. Although crocodiles have persisted under similar (or even more extreme) past scenarios of aridification (Brito et al. 2011; Drake et al. 2011), the present increase of local human activities (Brito et al. 2014) might exacerbate the negative impacts of future climate change. Growing human population densities, associated to potential increases in water extraction for domestic, pastoral and agricultural uses (Vale et al. 2015; Campos et al. 2016), represent possible threat factors that might contribute to future population fragmentation and local extinctions.

Conservation strategies are required for extenuating climate change and anthropogenic effects on the humid biodiversity hotspots (Brito et al. 2014), while connectivity conservation measures focused on preserving the current water networks could prevent exacerbated isolation of crocodile populations and other desert species. Detailed assessments of functional water corridors (through GPS/satellite tracking) are needed to identify the most important water connections for conservation and to assess the role of potential barriers (e.g., paved roads, dams) to dispersal and required local mitigation actions. Protection of aquatic habitats from excessive water use and contamination is needed to ensure long-term persistence of local aquatic organisms (Vale et al. 2015). Given that crocodiles are acknowledged as a valuable flagship species (Tellería et al. 2008; Shirley et al. 2009), assessments of ecotourism potential are needed to identify suitable water-bodies for these activities, which could promote the protection of crocodiles and associated humid habitats and water networks, as well as increasing the needed revenues of local communities (Santarém and Paiva 2015). Under these circumstances, our study delivers background information about potential climate-driven effects on population dynamics and connectivity, highlighting the needs for conserving aquatic species persisting in vulnerable and unstable water networks across arid and semi-arid regions.

DATA AVAILABILITY

Satellite images used in this study (see **Table E.2 in Appendix E**) are publically available at Global Visualization Viewer (GLOVIS; http://glovis.usgs.gov/). Microsatellite genotypes, water indexes, cost surfaces used in each landscape resistance scenario and all distance matrixes (genetic, geographic and resistance distances) that support the findings of this study are available from the corresponding author upon reasonable request.

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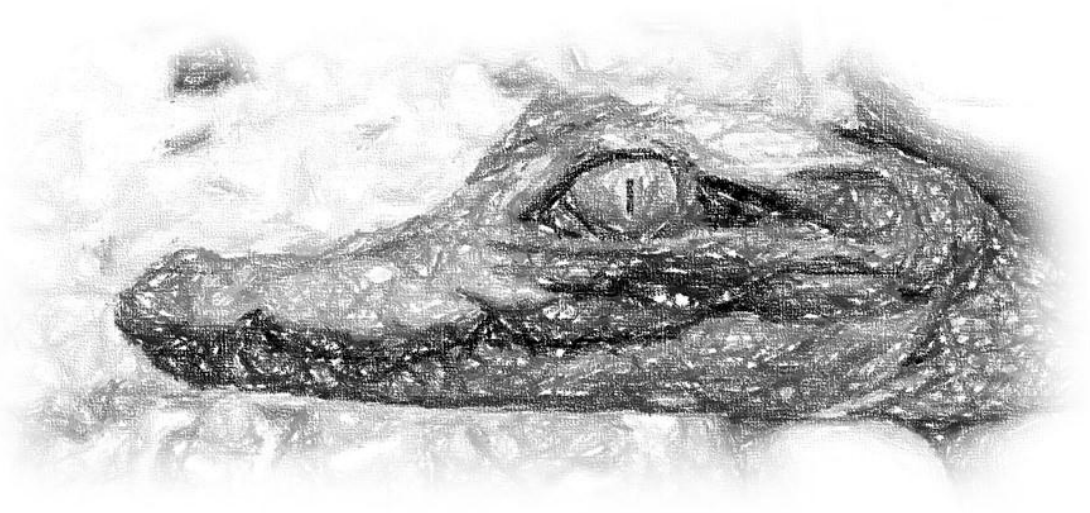

Juvenile of Crocodylus suchus*, Aîounet Nanâga, Mauritania*

Photo: JC Campos

CHAPTER VII

General discussion and concluding remarks

The planet will be here and we will be long gone. Just another failed mutation. Just another closed-end biological mistake. An evolutionary cul-de-sac. The planet will shake us off like a bad case of fleas.

George Carlin, Jammin' in New York (1992)

1. GENERAL DISCUSSION

The major objective of this thesis was to verify the importance of landscape connectivity and the application of Remote Sensing (RS) tools for assessing biodiversity patterns in desert environments. Four main goals were targeted for answering to this central objective: the assessment of the current state of structural connectivity methods for application in ecology, evolution and conservation; the evaluation of potential contributions of RS to the assessment of biodiversity distribution patterns in global drylands; the characterisation of landscape features for the assessment of local biodiversity patterns in the West Sahara-Sahel; and the assessment of the distribution and population connectivity of West African crocodiles in the West Sahara-Sahel. The first part of this chapter presents and discusses the major achievements of this thesis, concerning each of the four main goals. Then, research subjects and directions that should be addressed in the future are provided. Finally, the major conclusions of this thesis are presented.

1.1. KEY FINDINGS

1.1.1. CURRENT STATE OF STRUCTURAL CONNECTIVITY METHODS

A summary of graph-based methods and their respective extensions that are currently being used to estimate structural connectivity was presented in a work developed within this thesis (**Article I**). The major advantages and disadvantages of these methods were also scrutinised, which contributed to further understanding their most adequate applicability, and ultimately, to complement previous reviews on this subject.

The first graph-based approaches developed for measuring structural connectivity (Urban and Keitt 2001; Adriaensen et al. 2003), stands out as the main stimulus for the enormous expansion of this research field during the last years. A multitude of methods were developed since then, but a discrepancy on their usage is evident due mostly to complexity in running specific algorithms or lack of empirical studies exploring a particular method. Regular application of the most infrequently used methods (e.g., spatial interaction models, grains of connectivity, diffusion models) might spread their

utility and familiarisation amongst researchers, which would expose their revenues and constraints in different scenarios of structural connectivity. Also, selecting a single structural connectivity method for addressing a particular case study is not a straightforward task, especially because of several factors that may influence the methods performance, such as study area extent, life history traits of the focal species, landscape complexity, or availability of relevant demographic data (Dale and Fortin 2010; Vasudev et al. 2015). The most used methods, such as the least-cost paths (LCPs) and circuit flow (CF), have suffered cumulative developments which contributed to their increased spectrum of applicability. However, the intrinsic constraints of each method require additional research for developing potential frameworks that allow an efficient combination of outputs produced by distinct and complementary methods.

Combined outputs are capable of exploring multi-method features, such as high performance on multi-geographic scales (e.g., grains of connectivity), implementation of dispersal abilities (e.g., resistant kernel models, spatial interaction models), inclusion of behaviour complexity (e.g., individual-based models) and estimation of asymmetric flow rates (e.g., network flow, diffusion models). These implementations have the potential to improve the robustness of current landscape connectivity studies, and some studies have already taken advantage of such hybrid frameworks. The use of combined maps that synthesize results of different connectivity methods also allows generating informative maps, covering potential limitations of single method approaches and representing a valuable alternative and powerful tool for conservation planning.

1.1.2. Remote Sensing contributions to biodiversity studies in global drylands

Climatic and water availability indicators derived from RS data, allowed assessing the relationships between climatic and habitat factors with biodiversity distribution patterns in five drylands distributed across the globe (**Article II**). This was accomplished by analysing how the RS-derived indicators were correlated with modelled spatial patterns of vertebrate species richness (total and functional groups), information that was still lacking in drylands.

The study developed within this thesis, supported the validity of the Diversity II outputs for contrasting major patterns of biodiversity of vertebrates across drylands. The modelled biodiversity patterns were strongly related with water availability variables, such as precipitation and soil moisture, while contrasting results were obtained using

primary productivity indicators. These results highlight the importance of water resources for biodiversity across drylands, indicating that water availability might actually constitute the main driver of species richness of vertebrates in these ecosystems. Primary productivity constitutes an extremely important indicator for measuring changes and trends of ecosystem function, being frequently used for assessing processes of land degradation and desertification (del Barrio et al. 2016). Despite the low correlations verified for the primary productivity indicators, this work still recommends their application in biodiversity studies, by testing their relationships with different *taxa*, biodiversity metrics and spatial-temporal resolutions.

1.1.3. Landscape heterogeneity of the West Sahara-Sahel

An extensive dataset of field control points was used for land cover classifications with fine spatial resolution in the West Sahara-Sahel (comprising 23% of the Sahara-Sahel extent; **Article III**), an area that has been erroneously perceived as a homogenous bareland with poor levels of biodiversity in relation to other regions across the globe (Durant et al. 2012; Brito et al. 2014). Moreover, the Sahara-Sahel is usually classified as an extensive bare region in available RS-derived global land cover maps.

The study performed within this thesis demonstrated that much of the Sahara-Sahel land cover heterogeneity (concretely for the westernmost part of the Sahara) is currently under-represented. The region is composed by different types of dunes and rocky habitats with dissimilar geomorphological characteristics, classes that are normally uncategorized in available global land cover maps. Important landscape features for biodiversity were also detected, such as the lagoons associated to the major Mauritanian mountain systems, habitats that have been mentioned as micro-hotspots for biodiversity in need of global attention (Vale et al. 2015). Under this circumstance, this study denotes how a detailed land cover representation of the West Sahara-Sahel is pivotal for improving local biodiversity monitoring and conservation, as it was shown for the Critically Endangered addax (*Addax nasomaculatus*) and the mountain relict populations of the West African crocodile (**Article III**).

1.1.4. West African crocodiles in the Sahara-Sahel

Information about the distribution, population status, threat factors and population connectivity of the West African crocodile (*Crocodylus suchus*) was still incomplete or simply unavailable. In this thesis, two works were developed for filling the identified

gaps of knowledge (**Article IV** and **Article V**), whose corresponding key findings are discussed below.

1.1.4.1. CROCODILE DISTRIBUTION, POPULATION STATUS AND THREAT FACTORS

Before this study, crocodiles were known from 78 localities across the major mountains of Mauritania, including 60 of confirmed presence, 10 of possible presence, five of unconfirmed status, and three of confirmed extinction (Brito et al. 2011a,b). However, most of the crocodile populations distributed along the south-eastern part of Mauritania, particularly in the Afollé Mountain, remained poorly assessed. The work developed within this thesis (**Article IV**) allowed the identification of 26 localities where the presence of crocodiles was confirmed for the first time, increasing by 27% the total number of previously known localities of presence and possible presence of crocodiles in Mauritania (adding up to 96 currently known localities). Most of the new locations were detected in the Afollé mountain, increasing by 59% the number of known localities in this mountain. The considerable increase of crocodile records collected during this study exposed the current lack of sampling in the region, mostly related to the inaccessibility of the area and to the present scenarios of insecurity and regional conflicts that compromise local biodiversity surveys (Larémont 2011; Schleussner et al. 2016).

Previous studies have identified several threat factors possibly affecting crocodiles (Tellería et al. 2008; Brito et al. 2011a), but the identified threats were coarsely examined, highlighting the need for a quantitative assessment of the threats affecting crocodile populations and its habitats in Mauritania. The study developed within this thesis (**Article IV**) found that all the analysed crocodile locations face several threat factors. The different humid habitats in which crocodile populations persist are similarly threatened, being exposed to climatic and anthropogenic impacts. All the assessed habitats are affected by severe droughts and temperature extremes, a troublesome scenario taking into account that climate change forecasts conjecture future temperature increases and precipitation declines for the Sahara-Sahel (Held et al. 2005; Giannini 2015). Additionally, most of the crocodile habitats are affected by human pressures, in which water extractions for domestic use and nomadic grazing represent the most common ones. The intense exploitation of humid habitats for agricultural use and human and cattle consumption may lead to subsequent threats, such as excessive faecal contamination and water eutrophication (Tellería et al. 2008; Brito et al. 2011a). The combination of human activities with predicted climatic

oscillations for the region may promote local shortage of water availability or lead to the extinguishment of several water sources, further threatening the persistence of *C. suchus* populations and other water-dependent *taxa* in the region. The threats identified in this study may contribute to future assessments of *C. suchus* conservation status at both global and regional levels, which represents a major priority for the species given its current status of Not Evaluated by the IUCN (IUCN 2016).

1.1.4.2. HISTORICAL AND CONTEMPORARY POPULATION CONNECTIVITY

The effects of climatic variations on the spatial and temporal patterns of landscape connectivity and population dynamics in desert environments are still poorly understood. Given that the dispersion of crocodiles is mostly controlled by the local hydrological connectivity (Velo-Antón et al. 2014), this species was used as a model in a work developed within this thesis (**Article V**) for analysing how climatic and associated water availability fluctuations might influence spatial and temporal population dynamics and connectivity.

This study found that there is a major influence of geographic distance in shaping regional landscape connectivity and genetic patterns of *C. suchus* across time. Crocodiles presented general low genetic diversity and gene flow, whose populations were grouped according to distinct hydrographic sub-basins. The results found in this study were surprising, since it was expected a relation between the crocodiles genetic patterns and the landscape, rather than simple isolation by distance. Given that crocodiles are strongly dependent on water features to survive and to disperse, these patterns of genetic connectivity are probably influenced by fluctuations of water availability. The low levels of water availability during the dry seasons severely decrease water connectivity, amplifying the effects of isolation by distance. Contrarily, the abundance of seasonal water during the rainy seasons are able to connect most of the water bodies of the region. With such high levels of water availability, securing a strong pattern of water connectivity, the dispersal distance effects are still maintained.

The results obtained in this study revealed a complex dispersal dynamics of *C. suchus*, possibly related to species adaptive traits in the face of severe and variable conditions in the Sahara-Sahel. However, the future persistence of crocodiles in the region might be compromised due to the aforementioned climatic and human impacts affecting the water habitats in which they persevere (**Article IV**). Future studies should contemplate the implementation of conservation measures for protecting the natural habitats of

crocodiles and preventing the excessive isolation and potential extinction of their populations in the Sahara-Sahel.

1.2. FUTURE PROSPECTS

This thesis successfully demonstrates the importance of landscape connectivity and the application of RS tools to improve biodiversity studies in desert environments. However, there are still challenges to overcome in the near future.

The great progress in the field of structural landscape connectivity endorsed the development of new methodological tools and the upgrading of existing methods, but there is still room for improvements. The currently available panoply of structural connectivity methods (**Article I**), derived from a large array of theoretical foundations, presents multiple methodological alternatives that might not be consensually selected by researchers. Simplistic (e.g., LCPs) and more complex methods (individual-based models), are both restrained by intrinsic limitations that influence final outputs and consequent research interpretations. Perhaps future studies should refocus their efforts on intensive improvements of available methods (e.g., Etherington 2016), especially on the most widespread ones (e.g., LCPs, CF, graph-based methods), or on exploring multi-method approaches. Frameworks combining distinct methodologies show great promise since they can incorporate important aspects of connectivity that might not be comprised by single connectivity methods. Simplest approaches rely on the creation of maps assembling results of different connectivity methods for generating more informative outputs (e.g., Anderson et al. 2014), but combining different outputs may represent a valuable solution as well. For instance, graph-based centrality metrics might be explored with other connectivity methods (e.g., CF) to identify areas of intra and inter-patch connectivity (e.g., Rayfield et al. 2015), and might also represent a particularly useful solution for detecting important patches and corridors for connectivity in multi-species frameworks. However, the implementation of multi-method approaches might be a complex task for researchers. Research efforts should focus on providing tools and user-friendly platforms merging multiple methods in a simple way (e.g., Linkage Mapper; http://www.circuitscape.org/linkagemapper). Future connectivity studies would also benefit from reinforced collection of field observations (e.g., radio/GPS telemetry and mark-recapture approaches) and genetic data (e.g., microsatellites and SNPs). Acquiring extensive information about species dispersal

might be logistically challenging, but the robustness of connectivity studies would improve considerably. Moreover, methods that require large data availability, such as individual-based models, might be preferred in the long term, prompting their future exploration and enabling accurate connectivity frameworks in the future. Detailed parameterisation of cost surfaces stands out as another possible challenge for future studies. In this regard, RS can greatly contribute to this cause by providing exhaustive information about the landscape. Most certainly, the continuous progresses for improving current RS applications and derived products, and for obtaining high resolution data (both at temporal and spatial scales) and increased data accessibility, will contribute to better-quality landscape characterisations, and ultimately, to robust parameterisation of cost surfaces and accurate landscape connectivity studies.

In this thesis, it was successfully verified how biodiversity distribution patterns across global drylands are related with climatic factors and levels of primary productivity (**Article II**). Still, this study includes some uncertainty regarding identified species functional groups, due to the general lack of knowledge about species functional traits in drylands (Rodríguez and Ojeda 2014). Future studies should focus on additional data collection for a detailed discrimination of functional groups, such as the inclusion of physiological traits tied to species survival in drylands (e.g., water balance, metabolic rates and thermal tolerances; Foden et al. 2013), which represents a crucial step for improving the assessments of biodiversity-environment relationships. The work presented herein (**Article II**) can serve as an example for future biodiversity studies, which can differently explore the application of these indicators (e.g., testing different taxa, biodiversity metrics and spatial-temporal resolutions). These RS-indicators are now freely available for 22 global drylands (http://www.diversity2.info/products/), and further evaluations could clarify their significance for biodiversity assessments and monitoring (e.g., assess their adequacy to address Aichi Targets, such as sustainable consumption and production; see O'Connor et al. 2015). Moreover, the RS data used in this work covers the entire globe and is publically available (full archive of ENVISAT-MERIS, TRMM rainfall and ESA CCI soil moisture data), thus similar frameworks can be developed in other ecosystems.

In relation to land cover characterisations of the Sahara-Sahel, further studies should focus on collecting additional field data, particularly for the most under-sampled regions (e.g., easternmost part). These efforts might allow characterising additional land cover classes or improve the classification accuracy of classes predominantly distributed in the most arid regions. Moreover, using a larger ground validation dataset would help extrapolating the land cover classification scheme conducted for the West Sahara-

Sahel (**Article III**) to the entire Sahara-Sahel. However, the gargantuan dimensions of the Sahara (around 9,000,000 km^2) and the increased sampling constraints associated to the general remoteness and reduced accessibility, makes the collection of field data a complex task. Also, the rise of extremist groups (e.g., Al-Qaeda in the Islamic Maghreb) have sprawled numerous acts of violence in the region, such as armed attacks, kidnaps, slavery and oppression (Weiss 2016). These growing trends of insecurity and civil conflict in the Sahara-Sahel hinder further field surveys (Schleussner et al. 2016).

There are possible solutions for surpassing the lack of ground validation data, but one must account their associated limitations. Cross-validation recurring to existing regional and/or local land cover maps might represent the easiest solution, but not the most robust one, since the validation accuracy might considerably decrease according to non-overlapping spatio-temporal map scales and to incomparable land cover classes. Moreover, currently available maps might suffer from inadequate accuracies and frequent misclassifications, which would preclude an effective validation. Validation data derived from visual interpretations of satellite images is a feasible solution, but the process is limited by expert-based subjective selections of land cover categories (Foody 2002; Zhao et al. 2014). Publically available global and regional validation datasets [e.g., Global Observation for Forest Cover and Land Dynamics (GOFC - GOLD): http://www.gofcgold.wur.nl/; Miyazaki et al. 2011; Zhao et al. 2014] might constitute one of the most useful and promising solutions for improving future classification accuracies in the Sahara-Sahel. Also, local crowd-sourcing programmes that could endorse the collection and validation of data in the field by volunteers [e.g., Geo-Wiki Project (https://www.geo-wiki.org/); see also Fritz et al. 2009] remain a possible solution for the future. Nevertheless, there is still a lack of knowledge about RS concepts and foundations in most of the African countries, particularly in the Sahara-Sahel (see Klerk and Buchanan 2017). This lack of expertise delays the application of RS techniques in these regions, preventing its full exploration in different research fields, such as conservation (**Fig. 8.1**). Regional training and capacity building would probably contribute for incrementing the use of RS tools and improving national and regional RS variables for the Sahara-Sahel. A recent intergovernmental initiative formed in 2014 by the Group on Earth Observations, the AfriGEOSS (http://www.earthobservations.org/afrigeoss.php), constitutes an important step for disseminating and providing the accessibility to RS data across many African countries. Still, important countries of the Sahara are currently non-members of this initiative, such as Libya, Chad and Mauritania. Providing RS data, such as the derived land

cover map in this study (**Article III**), to local governmental entities could help improving future decision making in the management of local natural resources and possibly draw their attention for the potential of RS, which would result in higher investments on RS teaching and application (de Sherbinin et al. 2015).

The RS-derived variables developed in this thesis allowed identifying important landscape features for local biodiversity in the Sahara-Sahel region (**Article III**), such as the aquatic micro-hotspots associated to the major mountains of Mauritania (Vale et al. 2015). A large number of these aquatic habitats were assessed for detecting the presence of West African crocodiles and also potential threats affecting local biodiversity (**Article IV**). Notwithstanding the positive results obtained in this study, future challenges also emerged from these assessments. The considerable increase in the number of discovered crocodile localities clearly indicates the lack of sampling in the region. Future surveys should be focused in the collection of additional distribution data, particularly for the most under-sampled regions, where sampling efforts will probably allow discovering additional crocodile populations and aquatic habitats. The number of threats affecting crocodile populations and the habitats in which they endure, highlights the need of future conservation actions for the region. Conservation planning should be supported by solid data about the current state of water-bodies and their biodiversity value (Trape 2009; Vale et al. 2015). Therefore, future studies should focus on water quality assessments (e.g., measurements of water temperature, pH, organic suspended matter and nitrification levels) and on the identification of localised risks to biodiversity and human well-being. In fact, Mauritania stands out as one of the countries in the world with the highest incidences of malaria and diarrhoeal diseases, both responsible for 12% (around 4,000 casualties) of annual deaths in the country (World Health Organization; http://www.who.int/gho/countries/mrt/country_profiles/en/). These assessments would help on the identification of water-bodies needing urgent protection and on the delineation of conservation action protocols for the sustainable use of water-bodies by local communities (e.g., construction of water cisterns for facilitating water access by local people and reducing water contamination). Additionally, future efforts should focus on assessments of biodiversity status and trends in water-bodies (e.g., biodiversity measurements and monitoring through environmental DNA, identification of evolutionary significant units richness; Thomsen and Willerslev 2015; Groves et al. 2017), which would help identifying priority water sources for conservation. Future conservation frameworks should also envisage capacity building and environmental training, since local human resources are currently lacking knowledge, skills and equipment for performing biodiversity assessments (Brito

et al. 2016). Engaging local communities and governmental entities to define planning priorities and further investments on environmental teaching/training (e.g., local students, villagers, policy-makers), would contribute for establishing a solid conservation strategy with long-term success (Durant et al. 2014).

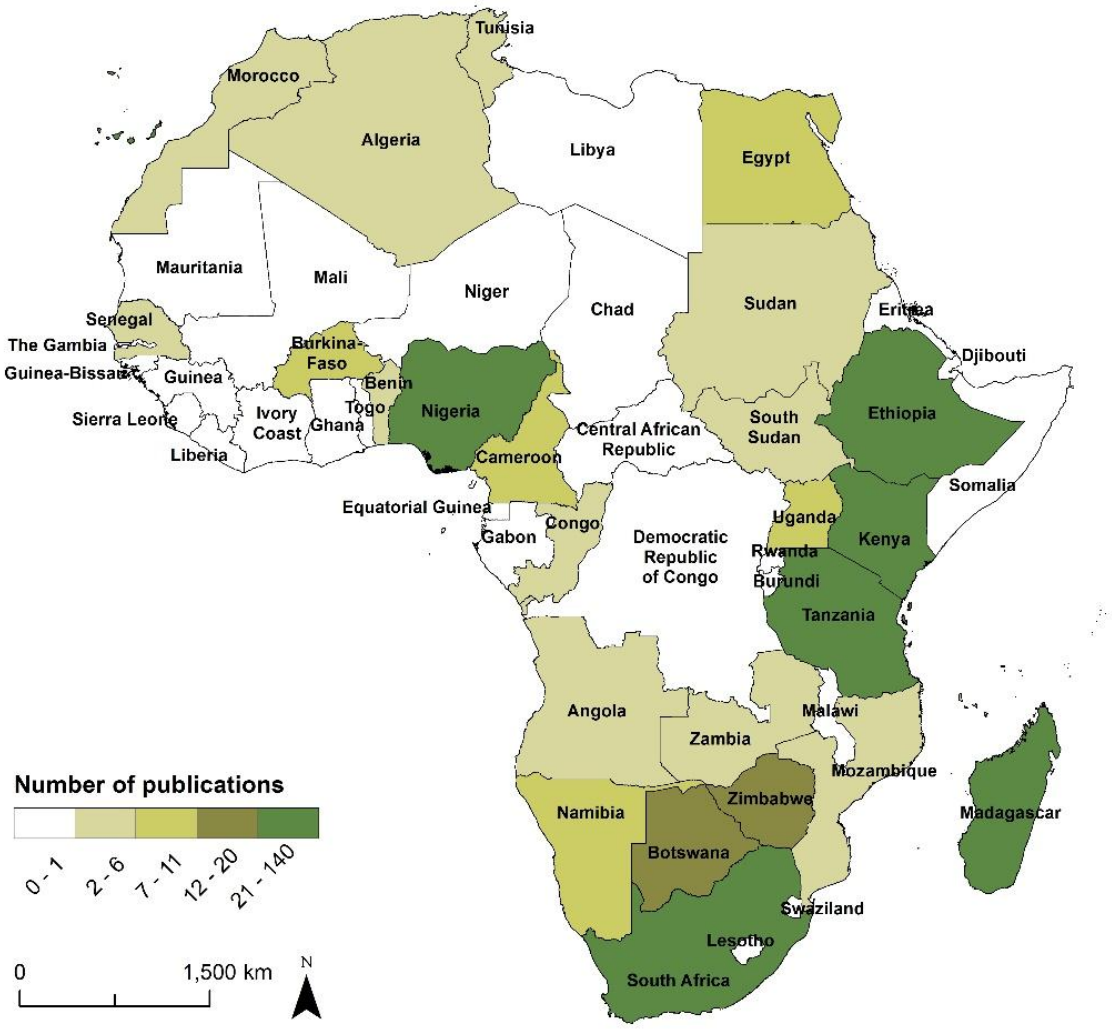

Fig. 8.1 - Number of peer-reviewed publications (N=580) integrating remote sensing and conservation in Africa (following the search criteria in Klerk and Buchanan 2017) and produced by authors with addresses in Africa. Data were extracted from Klerk and Buchanan (2017).

Besides the strategies needed to protect local aquatic biodiversity hotspots, connectivity conservation measures focused on preserving local water networks should be also conducted to prevent exacerbated isolation of relict populations of *C. suchus* (as it was observed in **Article V**). Future studies should comprise detailed assessments of functional water corridors for crocodiles (through GPS/satellite tracking), which would help selecting the most important water connections for conservation and to assess the role of potential barriers to dispersal (e.g., Read et al. 2007; Campbell et al. 2010). In this regard, roads have been mentioned as one physical obstacle for crocodiles, and field surveys have already registered run-over individuals during dispersal movements (Brito et al. 2011a,b; **Fig. 8.2**). The risk of road collision might be highly problematic for extremely isolated crocodile populations, whose survival might depend on periodical dispersal movements. For instance, gene flow estimations using microsatellite markers and landscape connectivity analyses (**Article V**) suggested genetic and hydrological connectivity, respectively, between the northern crocodile populations in the Tagant mountain and the Assaba populations in the south (**Fig. 8.3**). However, dispersing individuals might face high mortality risks due to a paved road located in the contact zone (the Djouk valley) between the two mountains. Given the accelerated pace of paved roads constructions in Mauritania during the last years (**Fig. 8.3**), local road-mitigation actions might be needed in the future.

Fig. 8.2 - A run-over sub-adult of *Crocodylus suchus* observed in Diawling National Park, Mauritania (photos by Teresa Abáigar, 03/02/2012)**.**

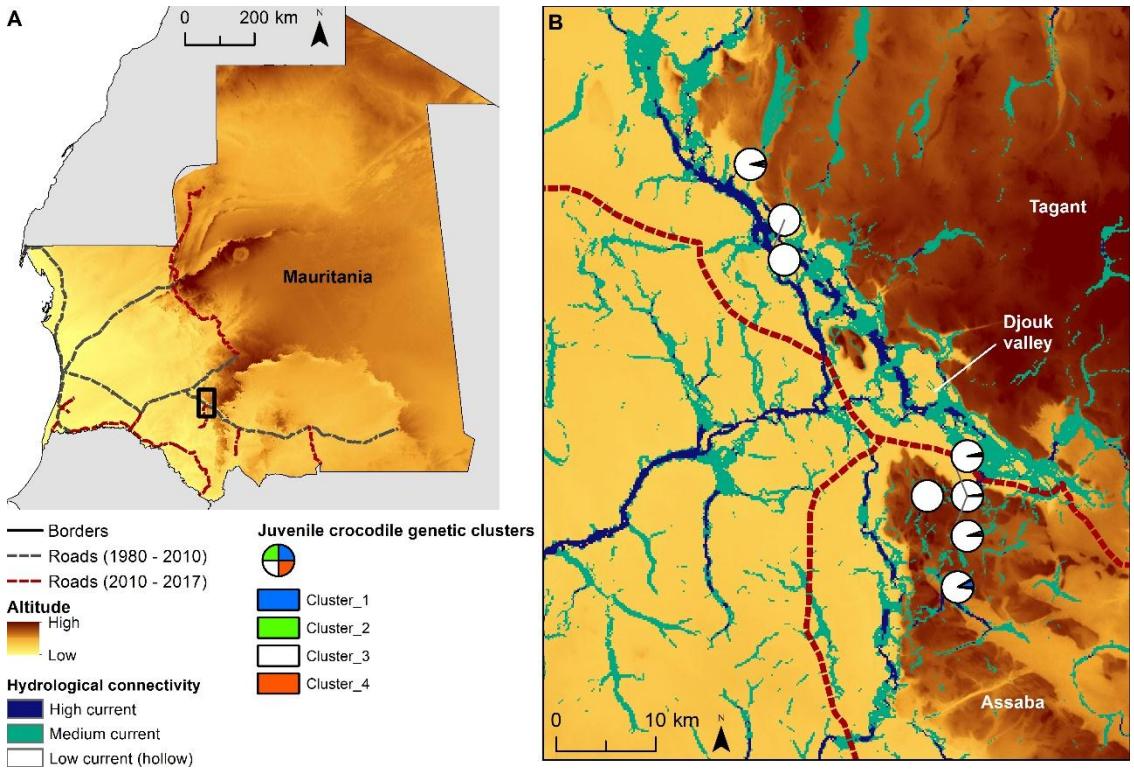

Fig. 8.3 - A) Growing trends of paved road constructions in Mauritania since the 1980s until now (GPS-tracks made by Biodeserts team during several fieldwork expeditions between 2003 and 2017); B) Zoom of a contact zone (Djouk valley) between the Tagant and Assaba mountains, illustrating the potential impacts of roads on local population connectivity of *C. suchus*. Hydrological connectivity was derived from CIRCUITSCAPE analyses in **Article V**, ranging between low (hollow) and high (blue) current. Genetic connectivity is exemplified by the clustering analyses of juvenile crocodile populations derived in **Article V.**

Despite the relevant information provided in this thesis regarding the distribution and population connectivity of *C. suchus* (**Article IV** and **Article V**), there are still considerable gaps of knowledge about the species biological, ecological and behavioural processes. Moreover, *C. suchus* is currently categorised as Not Evaluated by IUCN (IUCN 2016). Future studies comprising assessments of population trends and satellite tracking or mark-recapture approaches for clarifying possible sex/size-related biases in dispersal, might provide critical data for updating *C. suchus* conservation status and for delineating a conservation action plan for the species. The conservation of *C. suchus* populations might be highly beneficial for the region, bringing favourable conditions to both local biodiversity and local communities. Primarily, crocodiles are acknowledged as a valuable flagship species that could promote ecotourism activities (Tellería et al. 2008; Shirley et al. 2009). By increasing the economical incomes of local communities, these activities might encourage the protection of crocodiles and associated water-bodies. Lastly, *C. suchus* represents a

putative umbrella species (Velo-Antón et al. 2014), and its conservation would greatly benefit other aquatic species co-occurring in the same biodiversity micro-hotspots across the Sahara-Sahel.

1.3. CONCLUDING REMARKS

The major achievements of this thesis provide relevant insights about the importance of landscape connectivity for desert organisms and how current assessments of biodiversity patterns in desert environments can profit from the application of RS tools. This thesis outlined strengths and weaknesses of available structural connectivity methods and corresponding methodological developments, indicating possible implementations in ecology, evolution and conservation frameworks. Also, the potential contributions of RS for the assessment of regional and local biodiversity distribution patterns in global drylands and in the Sahara-Sahel, respectively, were successfully explored in this thesis. Finally, this thesis presented an interdisciplinary approach combining landscape connectivity methods, RS techniques and genetic analyses for assessing local distribution patterns and population connectivity of West African crocodiles in the West Sahara-Sahel. The major conclusions of this dissertation are presented below:

- Future landscape connectivity studies should focus on the development of integrative frameworks, combining complementary methods to better understand the relationships between landscape structure and species behaviour at structural and functional levels;

- Increased efforts on the development of computational resources and on gathering genetic and movement data will allow the employment of sophisticated methods to evaluate population connectivity and the preservation of overall landscape patterns for population stability and conservation;

- Remote Sensing variables related to water availability, such as precipitation and soil moisture, exhibit closer relations with vertebrate species richness (both total

and functional richness) in drylands, in comparison to estimates of primary productivity, rain-use efficiency and soil moisture-use efficiency;

- Distribution patterns of vertebrate species with small body size, and particularly amphibians, are better predicted using Remote Sensing indicators of water availability across drylands;

- Several land cover classes (N=18) covering the most arid regions of the West Sahara-Sahel (totalling 23% of the Sahara-Sahel extent), classes that are usually under-represented in available global land cover maps, were accurately classified in this study;

- The land-cover map derived herein provided detailed information about the landscape heterogeneity of the West Sahara-Sahel, constituting framework data for future conservation studies in the region;

- Several new crocodile localities (N=26) were discovered in Mauritania, increasing by 27% the current number of all known locations (adding up to N=96);

- Eleven threat factors affecting crocodile populations and associated habitats were identified, being droughts and temperature extremes (100% localities affected) and water extraction for domestic use and nomadic grazing (94%) the most frequent;

- Crocodiles are apparently vulnerable in the northernmost areas of Mauritania (particularly the isolated populations in the Tagant mountain), and future local conservation strategies are needed to assure the persistence of its fragile populations and their respective habitats;

- Crocodiles present high levels of genetic isolation in the northern mountains of Mauritania, reflecting the effects of limited water availability;

- Southern populations of crocodiles show patterns of populations connectivity, probably related with high water availability in those regions;

- Genetic differentiation of crocodiles are explained by an isolation by distance hypothesis

- Geographic distance might drive ecological and evolutionary traits of aquatic desert species, whose survival might be compromised by future climate change scenarios.

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APPENDIX A

Methodological advances in landscape connectivity: where are we and where to go?

TEXT A.1 - *Common algorithms used in Graph-only methods (G-OM)*

The G-OM may be performed using distinct algorithms, such as (i) nearest neighbour, (ii) minimum spawning tree, (iii) Gabriel graph, (iv) Delaunay triangulation and (v) centrality metrics. These algorithms are relatively well-accepted in ecological studies, although the latter is currently the most used one (see Urban and Keitt 2001; Minor and Urban 2008; Dale and Fortin 2010). Centrality metrics identify different levels of graph connectivity by evaluating the number of node connections (degree), the weighted distance from the focal node to all nodes of a graph (closeness) and the number/ratio of the shortest links that pass through a specific node or edge (betweenness).

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TEXT A.2 - *Calculation of Least-cost paths (LCPs)*

The first step to calculate LCPs involves assigning cost or resistance values to every pixel of a raster layer. The parameterized resistance surfaces can be directly included on connectivity analyses or be used to calculate cost weighted distances (CWD). The CWD is estimated by accounting mean cost values of the focal node and its neighbouring node, weighted by the Euclidean distance separating them, according to the following equation: CWD = [(cost focal pixel + cost neighbour pixel) / 2]] x Euclidean distance (Singleton et al. 2002). The result is a cost weighted distance

surface (CDWS) where each pixel is assigned with a cumulative cost per distance unit. The CDWS are then used to calculate LCPs through mathematical algorithms (see also Cherkasky et al. 1993), which determine the path based on the lowest cumulative resistance cost connecting a source to a target node.

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TEXT A.3 - *Theoretical background of Resistant Kernel Modelling*

The expected kernel density of dispersing individuals, i.e., the relative probability distribution of individual dispersion, is calculated in each pixel around the source, based on landscape resistance and dispersing ability. The method uses LCPs on source cells (e.g., sampling points) to derive a cost surface weighted by a user-defined distance dispersal threshold. An expected kernel density of dispersing individuals is constructed on a cost surface, through a movement function that predicts a negative relationship between density of individuals and movement cost (Riordan et al. 2016). Kernels surrounding source nodes are summed to interpolate relative density across all pixels. The interpolated density displays the probability of an individual dispersing from the focal source and arriving to any other point in the landscape, scaling the distance effect on connectivity (Compton et al. 2007; Cushman et al. 2013; Kool et al. 2013).

References

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TEXT A.4 - *Theoretical background of Current Flow*

Analogous to an electric circuit, electrical current can be interpreted as the expected net movement probabilities for random walkers (i.e., random dispersal movements). Current flow (individual's movement) moves through a graph of nodes (patches) connected by resistors (edges) within a conductive surface (landscape). One important property of electric circuits concerns the possibility of integrating parallel connections (resistors) that increase overall conductance (McRae 2006). This property can be easily transferred and interpreted from an ecological perspective, where a higher number of possible migration routes increase overall connectivity between nodes (see McRae 2006). Thus, the implementation of circuit methods is straightforward since conductance and/or resistance assigned to raster pixels (surface cost) have clear interpretations in terms of movement probabilities of the study organism through the habitat type encoded by the pixel (McRae et al. 2008).

References

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TABLE A.1 - ***Summary of the advantages and weaknesses of reviewed methods. A list of commonly used software for each method is also presented. The numbers in superscript correspond to the respective citation in the "References" section (see below). Names in italics denote the name of statistical packages.***

Method	Software	Advantages	Weaknesses
Graph-only methods	- Python (*NetworkX* [1]) - Conefor Sensinode[2] - UNICOR[3] - R [4] (*igraph*[5], *Graphab*[6]) - Connectivity Analysis Toolkit (CAT)[7]	- User-friendly - Evaluation of global connectivity	- Simplistic representation of the landscape - Poor statistical framework for hypothesis testing - Ambiguous interpretability when performing simulations - Disregard of direct dispersal among non-neighbouring nodes
Least-Cost Paths	- UNICOR[3] - ArcGIS[8] - QGIS[9] - Linkage Mapper[10] - R[4] (*gdistance*[11])	- User-friendly - Straightforward visual representation of landscapes - Spatially explicit representation of complex landscapes - Suitable at local scales	- Identifies only the most optimal routes - Strict one-pixel wide corridors - Assumes isotropic flow - No estimates of global connectivity
Least-Cost Corridors	- ArcGIS[8] - QGIS[9] - Linkage Mapper[10]	- Strong points identical to LCPs - Multi-pixel wide corridors	- Subjective cumulative costs thresholds - Identification of only most optimal routes - Assumes isotropic flow - No global connectivity estimates

TABLE A.1 - ***Continued.***

Method	Software	Advantages	Weaknesses
Least-Cost Transects	- Python customized scripts[12]	- Strong points identical to LCPs - Multi-pixel wide corridors - May integrate ecological data for design of suitable corridors for focal species	- Subjective buffer size selection - Identification of only most optimal routes - Assumes isotropic flow - Absence of global connectivity estimates
Resistant Kernel Modelling	- UNICOR[3]	- Synoptic method - Computationally efficient - Multi-pixel wide corridors - Allows inclusion of movement data to increase performance	- Requires the collection of biological and ecological data to be reliable - Assumes isotropic flow
Grains of Connectivity	- R [4] (*grainscape*[13])	- Multi-scale approach - Accounts different pixel sizes - Can be combined with distinct methods (e.g., LCPs, Current Flow)	- Poor statistical framework for hypothesis testing - Assumes isotropic flow - Hard to implement
Current Flow	- Circuitscape[14]*	- User-friendly - Straightforward visual representation of landscapes - Processing of all possible pathways - Multi-pixel wide corridors - Efficient identification of landscape bottlenecks	- Absence of global connectivity estimates - Assumes isotropic flow - Correlated random walks cannot be assessed

TABLE A.1 - ***Continued.***

Method	Software	Advantages	Weaknesses
Network Flow	- C++ (*LEMON*)[15]	**-** Incorporates measures of link capacity **-** Processing of all possible pathways - Estimates link permeability to particular amount of flow - Anisotropic method	**-** Strict one-pixel wide corridors - Harder to implement - Flow losses (e.g., mortality of dispersers) are not accounted
Spatial Interaction Models	- Any statistical software capable of doing model estimation and validation[16] - R[4] (*GenEtIt*[17])	- Anisotropic method **-** Explicit inclusion of genetic and demographic data to increase accuracy **-** Estimation of multiple parameters in a single empirical model	- Rely on parametric model assumptions - Computationally intensive and time consuming - Hard to implement - Lack of support by the scientific community
Individual-based Models	- Customized programming scripts (e.g., R script for Randomized Shortest Path[18] (RSP)) or RangeShifter[19] to apply the Stochastic Movement Simulator	**-** Integration of complex behavioural, demographic, genetic and movement properties **-** Multi-pixel wide corridors **-** Multi-scale approach **-** Trade-off between optimal and random movements (in case of RSPs) **-** Anisotropic method	**-** Requires a great deal of ecological data to parameterize accurately the analyses **-** Computationally intensive and time consuming **-** Requires mathematical and computational expertise (except in RangeShifter) **-** Time-consuming parameter fine-tuning for analyses

TABLE A.1 - ***Continued.***

Method	Software	Advantages	Weaknesses
Diffusion models (DF)	- COMSOL[20]	**-** Integration of ecological and demographic data **-** Computationally more efficient than IBMs **-** Multi-pixel wide corridors - Multi-scale approach - Anisotropic method	**-** Requires a great deal of ecological data to parameterize accurately the analyses **-** Still computationally intensive and time consuming compared with most methods **-** Lower flexibility compared with IBMs **-** Algorithms highly complex which require computational and mathematical expertise - Lack of support by the scientific community

*After being installed, it can be run also on QGIS and R.

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APPENDIX B

Remote Sensing indicators and vertebrate biodiversity distribution in global drylands: an assessment with ESA Diversity II products

TEXT B.1 - *Phenological and productivity parameters of the vegetation*

The bio-indicators were derived based on a phenological analysis of the seasonal behaviour of the vegetation at the pixel level for every (vegetation) year. **Fig. B.1** shows a phenology diagram explaining the derived phenological and productivity parameters. The diagram displays the temporal course of the MERIS fAPAR data during a 3-year period and subdivisions into different seasonal periods. The vegetation year includes the full yearly vegetation cycle, starting at the end of the preceding dry season and ending at the end of the following dry season (or in case of several green seasons during a year) at the begin of the statistically dominant green season. The vegetation year length varies with possible shifts of the green season starting time, which results from the high rainfall variability typical for drylands.

The vegetation year can be subdivided into different periods, limited by defined starting and ending points in time. The growing season includes the major peak(s), i.e., ascending and descending parts of the time series, and starts once a selected greenness threshold is surpassed on the way from the start of the vegetation year to the green peak. The dry season (brown parts of the curve in **Fig. B.1**) starts once a defined lower fAPAR threshold is passed. The thresholds depend on the seasonal amplitude and especially on the average level of the dry season values.

The bio-indicators are primarily based on the following NPP proxies:

- Average vegetation year fAPAR: Mean value of all fAPAR values within one full vegetation cycle, constituting a proxy for the annual NPP including the standing green biomass;
- Cyclic fraction fAPAR: The cyclic fraction of the vegetation is comprised of summed fAPAR values of the green peak(s) during a vegetation year, subtracting the non-cyclic base levels. The cyclic fraction fAPAR can be interpreted as the amount of NPP that is directly related to the annual cycle of the climatic vegetation growth factors, especially rainfall;
- Average dry season fAPAR: For the dry season the low fAPAR values after the green peak are averaged. The dry season greenness values reflect the portion of plants that remain green after senescence of the annual vegetation or grow new green leaves during the dry period. High dry season levels indicate the presence of shrubs, bushes and trees.

Below the fAPAR values for three years in **Fig. B.1**, the respective half-monthly rainfall and soil moisture values are shown. The dashed blue vertical lines are shifted by two months ahead of the fAPAR based vegetation year starts (dashed green lines), indicating that the temporal integration period of the rainfall data used to contrast the fAPAR data against, was shifted by two months ahead to account for the temporal delay observed between start of the rainy period and of start of major vegetation growth. The integration period for soil moisture was shifted back accordingly, but only by one month, again based on empirical observations.

Further details on the derivation of phenological and productivity parameters of the vegetation are available on the Products Users Handbook of the ESA Due Diversity II project (hwww.diversity2.info/products/documents/DEL8/DIV2_Products_User_Handbook_Drylands_v2.5.pdf).

TABLE B.1 - ***Description of bio-indicators. In the observed parameters, the RUE (Rain Use Efficiency) is based on MERIS fAPAR and TRMM rainfall data, and the SMUE (Soil moisture use efficiency) is based on MERIS fAPAR and CCI-SM (soil moisture) data. In the integration period, the Vegetation Year corresponds to the full vegetation cycle starting at the local start of season and ending after the dry season, the Cyclic Vegetation period corresponds to the period of the green peaks of the vegetation cycles, and the Dry Season corresponds to the season between the rainy seasons, in drylands usually with little or no vegetation growth (further details in Text B.1 in Appendix B). In the bio-indicator description, means and variation coefficients (%) are based on vegetation years starting on average from 2003 to2010, which involves globally the entire set of MERIS fAPAR data spanning from 2002 to 2012.***

Observed parameter	Integration period	Bio-indicator code	Bio-indicator name	Bio-indicator description
MERIS fAPAR	Vegetation Year	fAPAR veg M	Vegetation year average greenness	26 greenness classes; mean of 8 vegetation years average values
MERIS fAPAR	Vegetation Year	fAPAR veg V	Vegetation year greenness variability	26 greenness variability classes; variation coefficient of 8 vegetation year average values
MERIS fAPAR	Cyclic Vegetation period	fAPAR cyfr M	Cyclic vegetation greenness	26 greenness classes; mean of 8 cyclic fraction sum values
MERIS fAPAR	Cyclic Vegetation period	fAPAR cyfr V	Cyclic vegetation greenness variability	26 greenness variability classes; variation coefficient of 8 cyclic fraction average values
MERIS fAPAR	Dry season	fAPAR dry M	Dry season greenness	26 greenness classes; mean of 8 dry season average values
MERIS fAPAR	Dry season	fAPAR dry V	Dry season greenness variability	26 greenness variability classes; variation coefficient of 8 dry season average values

TABLE B.1 - ***Continued.***

Observed parameter	Integration period	Bio-indicator code	Bio-indicator name	Bio-indicator description
RUE	Vegetation Year	RUE veg M	Vegetation year RUE mean	26 RUE classes; mean of 8 vegetation year RUE values
RUE	Vegetation Year	RUE veg V	Vegetation year RUE variability	26 RUE variability classes; variation coefficient of 8 vegetation year RUE values
RUE	Cyclic Vegetation period	RUE cyfr M	Cyclic fraction RUE mean	26 RUE classes; mean of 8 cyclic fraction RUE values
RUE	Cyclic Vegetation period	RUE cyfr V	Cyclic fraction RUE variability	26 RUE variability classes; variation coefficient of 8 cyclic fraction RUE values
RUE	Dry season	RUE dry M	Dry season RUE mean	26 RUE classes; mean of 8 dry season RUE values
RUE	Dry season	RUE dry V	Dry season RUE variability	26 RUE classes; variation coefficient of 8 dry season RUE values
SMUE	Vegetation Year	SMUE veg M	Vegetation year SMUE	26 SMUE classes; mean of 8 vegetation year SMUE values
SMUE	Vegetation Year	SMUE veg	Vegetation year SMUE variability	26 SMUE variability classes; variation coefficient of 8 vegetation year SMUE values
SMUE	Cyclic Vegetation period	SMUE cyfr M	Cyclic fraction SMUE mean	26 SMUE classes; mean of 8 cyclic fraction SMUE values

TABLE B.1 - ***Continued.***

Observed parameter	Integration period	Bio-indicator code	Bio-indicator name	Bio-indicator description
SMUE	Cyclic Vegetation period	SMUE cyfr V	Cyclic fraction SMUE variability	26 SMUE variability classes; variation coefficient of 8 cyclic fraction SMUE values
SMUE	Dry season	SMUE dry M	Dry season SMUE mean	26 SMUE classes; mean of 8 dry season SMUE values
SMUE	Dry season	SMUE dry V	Dry season SMUE variability	26 SMUE variability classes; variation coefficient of 8 dry season SMUE values
TRMM Rainfall	Vegetation Year	Rain veg M	Vegetation year TRMM rainfall mean	26 TRMM rainfall classes; mean of 8 vegetation year rainfall sum values
TRMM Rainfall	Vegetation Year	Rain veg V	Vegetation year TRMM rainfall variability	26 TRMM rainfall variability classes; variation coefficient of 8 vegetation year rainfall sum values
TRMM Rainfall	Cyclic Vegetation period	Rain cyfr M	Cyclic fraction TRMM rainfall mean	26 TRMM rainfall classes; mean of 8 cyclic fraction rainfall sum values
TRMM Rainfall	Cyclic Vegetation period	Rain cyfr V	Cyclic fraction TRMM rainfall variability	26 TRMM rainfall variability classes; variation coefficient of 8 cyclic fraction rainfall sum values
CCI-SM	Vegetation Year	SM veg M	Vegetation year SM mean	26 SM classes; mean of 8 vegetation year SM average values

TABLE B.1 - ***Continued.***

Observed parameter	Integration period	Bio-indicator code	Bio-indicator name	Bio-indicator description
CCI-SM	Vegetation Year	SM veg V	Vegetation year SM variability	26 SM variability classes; variation coefficient of 8 vegetation year SM average values
CCI-SM	Cyclic Vegetation period	SM cyfr M	Cyclic fraction SM mean	26 SM classes; mean of 8 cyclic fraction SM average values
CCI-SM	Cyclic Vegetation period	SM cyfr V	Cyclic fraction SM variability	26 SM variability classes; variation coefficient of 8 cyclic fraction SM average values
MERIS fAPAR	Length of vegetation season	L veg M	Mean length of vegetation season	Mean of 8 vegetation season lengths

TABLE B.2 - ***Overview of sampling sizes for ecological models. Number of taxa (N taxa), number of observations (N obs), and average number of observations per taxa (Avg N) used to developed ecological niche-based models. Data presented for each taxonomic group and each dryland.***

		Australian	Caatinga	South-western Africa	Southern Europe	West Sudanian Savannah	Total
Amphibians	N taxa	17	18	15	26	15	91
	N obs	8,623	2,020	1,263	42,662	1,781	56,349
	Avg N	507	112	84	1,641	119	619
Reptiles	N taxa	195	13	119	37	53	417
	N obs	83,401	814	10,439	46,106	3,840	144,600
	Avg N	428	63	88	1,246	72	347
Mammals	N taxa	41	25	71	62	62	261
	N obs	25,575	2,120	5,501	190,532	5,562	229,290
	Avg N	624	85	77	3,073	90	879
Total	N taxa	253	56	205	125	130	739
	N obs	117,599	4,954	17,203	279,300	11,183	430,239
	Avg N	465	88	84	2,234	86	582

TABLE B.3 - ***Codes, names and source of ecogeographical variables used for ecological niche-based modelling. Climatic variables (Bio1 to Bio14) and Slope were used for all continental models, while land-cover types varied amongst continent (See Table B.4 for details on land-cover types).***

Code	Name	Source
Bio1	Annual Mean Temperature	Worldclim (http://www.worldclim.org/)
Bio5	Max Temperature of Warmest Month	Worldclim (http://www.worldclim.org/)
Bio6	Min Temperature of Coldest Month	Worldclim (http://www.worldclim.org/)
Bio12	Annual Precipitation	Worldclim (http://www.worldclim.org/)
Bio13	Precipitation of Wettest Month	Worldclim (http://www.worldclim.org/)
Bio14	Precipitation of Driest Month	Worldclim (http://www.worldclim.org/)
D00	Land-cover types (see Table B.4)	Globcover (http://due.esrin.esa.int/globcover/)
Slope	Slope	SRTM (http://srtm.usgs.gov/index.html)

TABLE B.4 - ***Land cover categories by continent used for developing ecological niche-based models.***

Continent	Code	Description
Africa	D03	Mosaic vegetation (50-70%) / cropland (20-50%)
	D07	Open (15-40%) broadleaved deciduous forest/woodland (>5m)
	D09	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)
	D10	Closed to open (>15%) herbaceous vegetation (grassland, savannahs or lichens/mosses)
	D14	Bare areas
	D15	Consolidated bare areas (hardpans, gravels, bare rock, stones, boulders)
	D16	Non-consolidated bare areas (sandy desert)
Australia	D03	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
	D05	Mosaic forest or shrubland (50-70%) / grassland (20-50%)
	D06	Mosaic grassland (50-70%) / forest or shrubland (20-50%)
	D01	Rainfed croplands
	D07	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)
	D08	Closed to open (>15%) herbaceous vegetation (grassland, savannahs or lichens/mosses)
	D09	Sparse (<15%) vegetation
Europe	D01	Rainfed croplands / herbaceous crops / shrub or tree crops
	D02	Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)
	D04	Closed (>40%) broadleaved deciduous forest (>5m)
	D06	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)
	D08	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)
	D12	Sparse (<15%) vegetation (grassland or shrubland)
South America	D01	Rainfed croplands and shrub or tree crops
	D02	Mosaic cropland (50-70%) / grassland/shrubland/forest (20-50%)
	D04	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
	D03	Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)
	D10	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)
	D05	Closed (>40%) broadleaved evergreen and/or semi-deciduous forest (>5m)

TABLE B.5 - ***Correlation scores between ecogeographical variables (EGVs) used for building the ecological models at a continental scale. EGVs are coded following Tables B.3 and B.4. The most significant correlation scores (>0.75; <-0.75) are highlighted in bold.***

Africa														
	bio12	**bio13**	**bio14**	**bio1**	**bio5**	**bio6**	**D03**	**D07**	**D09**	**D10**	**d014**	**d015**	**d016**	**slope**
bio12	1.00	**0.92**	0.56	-0.02	-0.57	0.55	-0.52	-0.54	-0.54	-0.35	0.59	**0.85**	0.68	0.16
bio13	**0.92**	1.00	0.32	0.08	-0.47	0.55	-0.57	-0.62	-0.61	-0.44	0.46	0.74	0.66	0.14
bio14	0.56	0.32	1.00	-0.06	-0.36	0.32	-0.21	-0.17	-0.12	-0.09	0.31	0.42	0.22	0.08
bio1	-0.02	0.08	-0.06	1.00	0.65	0.69	0.09	-0.23	0.17	-0.32	-0.11	0.02	-0.22	-0.33
bio5	-0.57	-0.47	-0.36	0.65	1.00	-0.04	0.50	0.39	0.57	0.24	-0.47	-0.47	-0.57	-0.34
bio6	0.55	0.55	0.32	0.69	-0.04	1.00	-0.34	-0.55	-0.31	-0.49	0.24	0.47	0.20	-0.09
D03	-0.52	-0.57	-0.21	0.09	0.50	-0.34	1.00	0.51	**0.84**	0.36	-0.29	-0.39	-0.47	-0.13
D07	-0.54	-0.62	-0.17	-0.23	0.39	-0.55	0.51	1.00	0.51	**0.93**	-0.32	-0.45	-0.55	-0.06
D09	-0.54	-0.61	-0.12	0.17	0.57	-0.31	**0.84**	0.51	1.00	0.31	-0.29	-0.43	-0.51	-0.18
D10	-0.35	-0.44	-0.09	-0.32	0.24	-0.49	0.36	**0.93**	0.31	1.00	-0.26	-0.30	-0.39	-0.01
d014	0.59	0.46	0.31	-0.11	-0.47	0.24	-0.29	-0.32	-0.29	-0.26	1.00	0.69	0.55	0.08
d015	**0.85**	0.74	0.42	0.02	-0.47	0.47	-0.39	-0.45	-0.43	-0.30	0.69	1.00	0.67	0.06
d016	0.68	0.66	0.22	-0.22	-0.57	0.20	-0.47	-0.55	-0.51	-0.39	0.55	0.67	1.00	0.11
slope	0.16	0.14	0.08	-0.33	-0.34	-0.09	-0.13	-0.06	-0.18	-0.01	0.08	0.06	0.11	1.00

TABLE B.5 - ***Continued.***

Australia														
	bio12	**bio13**	**bio14**	**bio1**	**bio5**	**bio6**	**D01**	**D03**	**D05**	**D06**	**D07**	**D08**	**D09**	**slope**
bio12	1.00	**0.89**	0.41	0.00	-0.47	0.40	0.50	-0.54	-0.10	-0.18	-0.42	0.39	0.50	0.42
bio13	**0.89**	1.00	-0.02	0.39	-0.12	0.73	0.33	-0.44	-0.14	-0.21	-0.41	0.18	0.33	0.23
bio14	0.41	-0.02	1.00	**-0.80**	**-0.82**	-0.60	0.46	-0.37	0.04	0.00	-0.14	0.52	0.46	0.47
bio1	0.00	0.39	**-0.80**	1.00	**0.83**	**0.82**	-0.31	0.26	-0.08	-0.08	-0.05	-0.42	-0.31	-0.30
bio5	-0.47	-0.12	**-0.82**	**0.83**	1.00	0.42	-0.50	0.54	0.01	0.04	0.18	-0.53	-0.50	-0.42
bio6	0.40	0.73	-0.60	**0.82**	0.42	1.00	-0.04	-0.14	-0.14	-0.16	-0.24	-0.19	-0.04	-0.14
D01	0.50	0.33	0.46	-0.31	-0.50	-0.04	1.00	-0.31	0.28	0.20	-0.06	0.56	1.00	0.34
D03	-0.54	-0.44	-0.37	0.26	0.54	-0.14	-0.31	1.00	0.17	0.15	0.38	-0.33	-0.31	-0.21
D05	-0.10	-0.14	0.04	-0.08	0.01	-0.14	0.28	0.17	1.00	**0.78**	0.61	0.35	0.28	0.05
D06	-0.18	-0.21	0.00	-0.08	0.04	-0.16	0.20	0.15	**0.78**	1.00	0.70	0.31	0.20	-0.02
D07	-0.42	-0.41	-0.14	-0.05	0.18	-0.24	-0.06	0.38	0.61	0.70	1.00	0.07	-0.06	-0.15
D08	0.39	0.18	0.52	-0.42	-0.53	-0.19	0.56	-0.33	0.35	0.31	0.07	1.00	0.56	0.35
D09	0.50	0.33	0.46	-0.31	-0.50	-0.04	1.00	-0.31	0.28	0.20	-0.06	0.56	1.00	0.34
slope	0.42	0.23	0.47	-0.30	-0.42	-0.14	0.34	-0.21	0.05	-0.02	-0.15	0.35	0.34	1.00

TABLE B.5 - ***Continued.***

Europe													
	bio12	**bio13**	**bio14**	**bio1**	**bio5**	**bio6**	**D01**	**D02**	**D04**	**D06**	**D08**	**d012**	**slope**
bio12	1.00	**0.93**	**0.85**	0.03	-0.36	-0.36	-0.04	0.08	0.24	0.30	0.22	0.23	0.46
bio13	**0.93**	1.00	0.67	0.01	-0.30	-0.30	-0.05	0.04	0.18	0.28	0.16	0.18	0.45
bio14	**0.85**	0.67	1.00	-0.06	-0.42	-0.42	-0.03	0.10	0.26	0.17	0.26	0.25	0.36
bio1	0.03	0.01	-0.06	1.00	**0.82**	**0.82**	-0.56	-0.45	-0.12	0.18	-0.05	-0.13	-0.01
bio5	-0.36	-0.30	-0.42	**0.82**	1.00	1.00	-0.52	-0.50	-0.31	-0.09	-0.25	-0.29	-0.19
bio6	-0.36	-0.30	-0.42	**0.82**	1.00	1.00	-0.52	-0.50	-0.31	-0.09	-0.25	-0.29	-0.19
D01	-0.04	-0.05	-0.03	-0.56	-0.52	-0.52	1.00	**0.91**	0.52	0.31	0.47	0.51	-0.06
D02	0.08	0.04	0.10	-0.45	-0.50	-0.50	**0.91**	1.00	**0.76**	0.54	0.73	**0.75**	-0.02
D04	0.24	0.18	0.26	-0.12	-0.31	-0.31	0.52	**0.76**	1.00	**0.80**	**0.99**	**0.99**	0.04
D06	0.30	0.28	0.17	0.18	-0.09	-0.09	0.31	0.54	**0.80**	1.00	**0.83**	**0.77**	0.10
D08	0.22	0.16	0.26	-0.05	-0.25	-0.25	0.47	0.73	**0.99**	**0.83**	1.00	**0.97**	0.03
d012	0.23	0.18	0.25	-0.13	-0.29	-0.29	0.51	**0.75**	**0.99**	**0.77**	**0.97**	1.00	0.04
slope	0.46	0.45	0.36	-0.01	-0.19	-0.19	-0.06	-0.02	0.04	0.10	0.03	0.04	1.00

TABLE B.5 - ***Continued.***

South America													
	bio12	**bio13**	**bio14**	**bio1**	**bio5**	**bio6**	**D01**	**D02**	**D03**	**D04**	**D05**	**D10**	**slope**
bio12	1.00	**0.92**	0.71	0.58	0.34	0.68	0.49	-0.12	-0.22	-0.40	-0.52	0.17	-0.14
bio13	**0.92**	1.00	0.42	0.65	0.42	0.73	0.41	-0.16	-0.26	-0.43	-0.53	0.17	-0.14
bio14	0.71	0.42	1.00	0.17	0.00	0.30	0.39	-0.04	-0.08	-0.19	-0.30	0.06	-0.03
bio1	0.58	0.65	0.17	1.00	**0.89**	**0.96**	0.34	-0.16	-0.28	-0.41	-0.34	0.18	-0.44
bio5	0.34	0.42	0.00	**0.89**	1.00	0.74	0.21	-0.13	-0.27	-0.31	-0.11	0.08	-0.54
bio6	0.68	0.73	0.30	**0.96**	0.74	1.00	0.42	-0.14	-0.26	-0.41	-0.43	0.24	-0.36
D01	0.49	0.41	0.39	0.34	0.21	0.42	1.00	0.31	0.23	-0.02	-0.26	0.03	-0.18
D02	-0.12	-0.16	-0.04	-0.16	-0.13	-0.14	0.31	1.00	0.70	0.53	0.26	-0.03	-0.02
D03	-0.22	-0.26	-0.08	-0.28	-0.27	-0.26	0.23	0.70	1.00	0.67	0.24	-0.04	0.04
D04	-0.40	-0.43	-0.19	-0.41	-0.31	-0.41	-0.02	0.53	0.67	1.00	0.61	-0.09	0.06
D05	-0.52	-0.53	-0.30	-0.34	-0.11	-0.43	-0.26	0.26	0.24	0.61	1.00	-0.16	-0.06
D10	0.17	0.17	0.06	0.18	0.08	0.24	0.03	-0.03	-0.04	-0.09	-0.16	1.00	0.06
slope	-0.14	-0.14	-0.03	-0.44	-0.54	-0.36	-0.18	-0.02	0.04	0.06	-0.06	0.06	1.00

TABLE B.6 - ***Correlation scores between ecogeographical variables (EGVs) and bio-indicators. EGVs are coded following Tables B.3 and B.4. fAPAR, rainfall, RUE, SM and SMUE are coded according to the aggregations of different productivity periods. The different productivity periods correspond to the cyclic fraction (cyfr), dry season (dry) and vegetation year (veg). All bio-indicators were temporally aggregated between 2002-2012 based on the mean (M) and variation (V) statistics. The most significant correlation scores (>0.75; <-0.75) are highlighted in bold.***

	fAPAR cyfr		**fAPAR dry**		**fAPAR veg**		**Rain cyfr**		**Rain veg**		**RUE cyfr**		**RUE dry**		**RUE veg**		**SM cyfr**		**SM veg**		**SMUE cyfr**		**SMUE dry**		**SMUE veg**		**L veg**
	M	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**
Australian																											
Bio1	-0.20	0.24	0.05	-0.01	-0.07	0.08	-0.01	0.22	0.14	0.27	0.39	-0.47	0.32	-0.07	0.05	-0.24	0.03	-0.68	0.66	-0.71	0.55	0.21	0.18	0.19	-0.06	0.10	0.04
Bio5	-0.35	0.37	-0.09	0.12	-0.25	0.23	-0.19	0.02	0.30	0.06	0.48	-0.52	0.41	-0.18	0.16	-0.39	0.19	-0.67	0.58	-0.71	0.44	0.12	0.22	0.04	0.07	-0.09	0.21
Bio6	-0.18	0.20	-0.02	-0.01	-0.14	0.15	-0.21	-0.10	0.20	-0.03	0.03	-0.22	0.21	-0.11	0.02	-0.25	0.13	-0.17	0.19	-0.18	0.05	0.14	0.02	0.02	-0.01	-0.10	0.18
Bio12	0.64	-0.52	0.56	-0.47	0.73	-0.64	0.71	**0.79**	-0.65	**0.78**	-0.26	0.22	-0.37	0.51	-0.42	0.65	-0.65	-0.04	0.27	-0.02	0.42	0.28	-0.14	0.58	-0.50	**0.75**	-0.70
Bio13	0.46	-0.32	0.49	-0.36	0.59	-0.47	0.56	0.71	-0.46	0.73	-0.03	0.02	-0.17	0.40	-0.31	0.45	-0.50	-0.27	0.52	-0.28	0.60	0.35	-0.05	0.56	-0.42	0.67	-0.53
Bio14	0.33	-0.29	0.08	-0.09	0.22	-0.20	0.18	0.02	-0.25	-0.01	-0.35	0.45	-0.33	0.16	-0.11	0.33	-0.18	0.54	-0.43	0.61	-0.28	-0.09	-0.14	-0.02	-0.06	0.09	-0.20
D01	-0.04	-0.01	0.11	-0.16	0.05	-0.13	0.11	0.34	-0.06	0.41	0.10	-0.36	0.16	0.00	-0.07	-0.10	-0.11	-0.53	0.34	-0.60	0.21	0.22	0.04	0.21	-0.18	0.19	-0.13
D03	0.02	-0.06	0.20	-0.18	0.17	-0.24	0.32	0.53	-0.21	0.55	0.19	-0.39	0.10	0.10	-0.10	0.02	-0.25	-0.70	0.58	**-0.75**	0.54	0.16	0.11	0.35	-0.23	0.35	-0.29
D05	-0.50	0.48	-0.31	0.30	-0.51	0.53	-0.59	-0.62	0.55	-0.57	0.06	-0.19	0.38	-0.32	0.26	-0.50	0.51	-0.03	-0.04	0.05	-0.28	-0.11	0.10	-0.33	0.32	-0.53	0.57
D06	-0.50	0.52	-0.37	0.37	-0.54	0.59	-0.62	-0.63	0.61	-0.61	0.27	-0.20	0.39	-0.37	0.31	-0.53	0.55	0.00	-0.03	0.00	-0.15	-0.13	0.14	-0.39	0.38	-0.56	0.61
D07	-0.41	0.42	-0.44	0.44	-0.53	0.52	-0.48	-0.49	0.53	-0.50	0.45	-0.14	0.29	-0.41	0.39	-0.47	0.51	-0.13	-0.02	-0.30	-0.06	-0.13	0.20	-0.43	0.45	-0.50	0.52
D08	-0.28	0.38	-0.26	0.29	-0.35	0.46	-0.47	-0.49	0.48	-0.48	0.28	-0.04	0.25	-0.26	0.23	-0.34	0.41	0.14	-0.06	0.11	-0.02	-0.06	0.12	-0.30	0.30	-0.40	0.46
D09	0.21	-0.14	0.32	-0.24	0.33	-0.19	0.09	0.07	-0.11	0.06	-0.10	0.12	-0.15	0.33	-0.25	0.33	-0.17	0.14	-0.14	0.12	-0.09	0.14	-0.13	0.25	-0.22	0.26	-0.16
Slope	0.15	-0.16	0.23	-0.18	0.25	-0.21	0.17	0.18	-0.16	0.17	-0.06	0.06	-0.13	0.24	-0.18	0.25	-0.21	0.09	-0.03	0.10	0.01	0.03	-0.08	0.20	-0.18	0.21	-0.21

TABLE B.6 - *Continued.*

	fAPAR cyfr		fAPAR dry		fAPAR veg		Rain cyfr		Rain veg		RUE cyfr		RUE dry		RUE veg		SM cyfr		SM veg		SMUE cyfr		SMUE dry		SMUE veg		L veg
	M	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**
Caatinga																											
Bio1	0.24	-0.07	-0.16	-0.19	0.03	0.05	-0.30	0.46	0.29	0.46	0.31	-0.09	-0.21	-0.38	-0.15	-0.34	-0.09	-0.15	0.26	-0.24	0.35	0.30	-0.09	-0.06	-0.10	0.15	0.09
Bio5	0.21	-0.20	-0.20	-0.23	-0.01	-0.08	-0.18	0.33	0.01	0.33	0.02	0.00	-0.27	-0.35	-0.18	-0.26	-0.15	-0.17	0.29	-0.24	0.35	0.28	-0.16	-0.09	-0.05	0.11	0.11
Bio6	0.22	0.14	-0.04	-0.04	0.09	0.21	-0.36	0.49	0.59	0.49	0.61	-0.16	-0.06	-0.30	-0.04	-0.33	0.05	-0.06	0.18	-0.14	0.29	0.24	0.05	0.02	-0.09	0.16	0.08
Bio12	0.28	-0.14	0.47	-0.01	0.52	-0.25	0.14	0.62	0.19	0.62	0.21	-0.18	-0.12	0.03	0.00	-0.09	-0.12	0.21	0.04	0.18	0.11	0.21	-0.11	0.32	0.01	0.36	-0.14
Bio13	0.32	-0.17	0.20	-0.19	0.35	-0.13	-0.16	**0.85**	0.36	**0.84**	0.39	-0.30	-0.27	-0.34	-0.21	-0.42	-0.20	0.14	0.02	0.06	0.18	0.26	-0.21	0.13	-0.25	0.26	-0.18
Bio14	-0.17	0.28	0.38	0.37	0.15	0.02	0.25	-0.38	0.03	-0.38	0.02	0.08	0.37	0.60	0.40	0.42	0.24	0.08	-0.18	0.17	-0.28	-0.16	0.28	0.28	0.31	0.09	-0.04
D01	0.08	-0.20	0.09	-0.21	0.12	-0.21	0.12	-0.02	-0.21	-0.02	-0.22	0.12	-0.15	0.04	-0.19	0.14	-0.16	0.03	0.32	0.04	0.32	0.06	-0.05	0.06	0.05	0.07	0.18
D02	-0.11	0.06	-0.14	-0.14	-0.19	0.06	-0.19	-0.12	0.07	-0.12	0.06	-0.01	0.02	-0.06	-0.08	-0.04	0.03	-0.08	-0.07	-0.09	-0.05	-0.09	0.02	-0.10	-0.14	-0.12	0.00
D03	-0.23	0.02	-0.24	-0.07	-0.33	0.04	-0.09	-0.17	-0.04	-0.17	-0.06	-0.09	0.02	-0.12	-0.03	-0.10	0.03	-0.08	0.06	-0.08	0.03	-0.18	0.04	-0.20	0.00	-0.24	0.12
D04	0.00	-0.04	-0.38	-0.22	-0.27	0.10	-0.31	0.05	0.09	0.05	0.08	-0.03	-0.16	-0.33	-0.22	-0.25	-0.09	-0.20	0.03	-0.26	0.06	0.07	-0.13	-0.24	-0.21	-0.11	-0.03
D05	0.19	-0.34	-0.12	-0.21	0.08	-0.19	-0.06	0.11	-0.39	0.11	-0.39	0.14	-0.31	-0.19	-0.24	-0.06	-0.22	0.06	0.11	0.01	0.15	0.15	-0.27	-0.12	-0.09	0.02	-0.03
D10	0.07	-0.02	0.01	0.14	0.06	0.00	0.07	0.06	-0.04	0.06	-0.04	0.02	0.01	-0.01	0.13	0.00	0.02	0.04	0.02	0.04	0.01	0.08	-0.01	0.01	0.13	0.05	0.00
Slope	0.09	-0.10	0.19	-0.03	0.20	-0.12	0.15	0.01	-0.06	0.01	-0.06	0.08	-0.06	0.14	-0.05	0.15	-0.10	0.10	-0.06	0.12	-0.06	0.06	-0.08	0.14	-0.05	0.12	-0.11
SW-Africa																											
Bio1	0.12	0.14	-0.04	0.02	0.12	0.18	-0.15	0.01	0.22	-0.01	0.43	0.05	0.14	-0.08	0.05	-0.04	0.18	-0.30	0.42	-0.40	0.42	0.37	-0.05	0.02	0.01	0.09	0.16
Bio5	-0.25	0.27	-0.19	0.20	-0.25	0.29	-0.23	-0.32	0.22	-0.31	0.00	-0.12	0.27	-0.16	0.19	-0.26	0.29	-0.27	0.23	-0.31	0.15	-0.03	0.14	-0.16	0.20	-0.22	0.28
Bio6	0.18	0.06	0.04	-0.06	0.18	0.09	-0.10	0.09	0.17	0.08	0.42	0.09	0.05	0.01	-0.03	0.04	0.09	-0.12	0.24	-0.22	0.24	0.35	-0.11	0.08	-0.06	0.14	0.08
Bio12	0.61	-0.71	0.55	-0.57	0.61	**-0.79**	0.74	**0.80**	-0.73	**0.81**	-0.56	0.11	-0.68	0.47	-0.56	0.63	**-0.78**	0.31	-0.23	0.62	-0.08	0.13	-0.27	0.52	-0.57	0.66	**-0.77**
Bio13	0.71	-0.66	0.43	-0.48	0.71	-0.69	0.66	**0.79**	-0.61	**0.78**	-0.18	0.23	-0.63	0.35	-0.45	0.63	-0.66	0.12	0.05	0.37	0.21	0.35	-0.29	0.45	-0.48	0.70	-0.70
Bio14	-0.05	-0.22	0.26	-0.20	-0.05	-0.30	0.25	0.14	-0.33	0.18	-0.66	-0.16	-0.20	0.27	-0.21	0.13	-0.31	0.40	-0.53	0.57	-0.52	-0.35	0.00	0.18	-0.19	0.04	-0.27
D01	-0.40	0.51	-0.35	0.39	-0.40	0.55	-0.51	-0.50	0.56	-0.52	0.62	-0.13	0.46	-0.33	0.37	-0.42	0.52	-0.13	0.18	-0.51	0.19	-0.08	0.17	-0.35	0.38	-0.44	0.54
D03	-0.21	0.34	-0.24	0.23	-0.21	0.38	-0.35	-0.31	0.38	-0.31	0.39	-0.11	0.32	-0.24	0.22	-0.30	0.38	-0.16	0.31	-0.36	0.31	0.04	0.10	-0.23	0.22	-0.27	0.37
D05	-0.24	0.33	-0.35	0.38	-0.24	0.38	-0.33	-0.32	0.36	-0.35	0.60	-0.07	0.33	-0.33	0.36	-0.28	0.41	-0.18	0.29	-0.47	0.35	-0.04	0.17	-0.35	0.37	-0.30	0.36
D06	0.11	0.03	0.09	-0.11	0.11	0.02	-0.02	0.06	0.10	0.06	0.19	0.05	0.00	0.07	-0.08	0.05	-0.02	-0.02	0.20	-0.10	0.21	0.19	-0.09	0.10	-0.12	0.10	0.01
D07	0.30	-0.48	0.41	-0.44	0.30	-0.54	0.47	0.50	-0.51	0.53	-0.53	0.01	-0.48	0.35	-0.45	0.36	-0.55	0.35	-0.36	0.57	-0.29	-0.06	-0.21	0.36	-0.43	0.36	-0.52
D08	0.18	-0.41	0.19	-0.19	0.18	-0.42	0.33	0.30	-0.47	0.34	-0.58	-0.03	-0.35	0.19	-0.19	0.23	-0.36	0.32	-0.36	0.57	-0.36	-0.17	-0.11	0.15	-0.19	0.17	-0.41
D09	-0.55	0.63	-0.35	0.41	-0.55	0.67	-0.65	-0.74	0.64	**-0.76**	0.31	0.00	0.59	-0.29	0.39	-0.49	0.67	-0.21	0.13	-0.51	-0.07	-0.12	0.21	-0.34	0.41	-0.55	0.67
Slope	0.17	-0.12	0.14	-0.08	0.17	-0.13	0.11	0.11	-0.07	0.08	0.04	0.23	-0.12	0.15	-0.08	0.22	-0.14	0.03	-0.04	0.05	-0.03	0.12	-0.08	0.13	-0.09	0.17	-0.13

TABLE B.6 - *Continued.*

	fAPAR cyfr		fAPAR dry		fAPAR veg		Rain cyfr		Rain veg		RUE cyfr		RUE dry		RUE veg		SM cyfr		SM veg		SMUE cyfr		SMUE dry		SMUE veg		L veg
	M	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**
S-Europe																											
Bio1	0.15	0.04	-0.08	-0.01	0.01	0.15	0.17	-0.23	0.41	-0.30	0.54	0.24	0.18	0.04	0.03	0.31	0.31	-0.29	0.19	-0.38	0.32	0.22	0.02	0.01	-0.02	0.16	0.08
Bio5	0.05	0.18	-0.33	0.09	-0.28	0.31	0.10	-0.34	0.40	-0.40	0.50	0.18	0.28	-0.19	0.08	0.34	0.34	-0.36	0.30	-0.45	0.45	0.16	0.10	-0.19	0.05	-0.06	0.17
Bio6	0.21	-0.05	0.08	-0.08	0.19	0.04	0.17	-0.09	0.36	-0.16	0.48	0.25	0.09	0.16	-0.02	0.23	0.23	-0.19	0.13	-0.27	0.24	0.24	-0.04	0.13	-0.08	0.29	0.00
Bio12	0.14	-0.29	0.47	-0.21	0.51	-0.35	0.08	0.70	0.06	0.73	0.08	-0.09	-0.26	0.20	-0.10	-0.14	-0.14	0.31	-0.11	0.35	-0.14	0.09	-0.26	0.34	-0.18	0.36	-0.26
Bio13	0.15	-0.26	0.45	-0.24	0.50	-0.31	0.11	0.55	0.20	0.54	0.25	-0.03	-0.18	0.26	-0.11	-0.03	-0.03	0.18	-0.07	0.20	-0.07	0.10	-0.21	0.35	-0.20	0.38	-0.23
Bio14	-0.04	-0.19	0.26	-0.04	0.21	-0.27	-0.11	0.43	-0.49	0.52	-0.60	-0.20	-0.29	0.05	-0.06	-0.35	-0.35	0.36	-0.27	0.47	-0.42	-0.13	-0.16	0.13	-0.02	0.02	-0.17
D01	-0.20	0.11	0.10	-0.04	-0.04	-0.04	0.04	-0.08	0.18	-0.10	0.20	-0.19	0.10	0.16	-0.03	0.02	0.02	-0.19	0.04	-0.18	0.07	-0.15	0.07	0.18	-0.05	0.06	-0.05
D03	-0.23	0.07	0.15	-0.01	-0.01	-0.11	-0.02	-0.06	0.03	-0.07	0.03	-0.23	0.04	0.20	0.00	-0.07	-0.07	-0.09	-0.06	-0.06	-0.09	-0.20	0.06	0.20	-0.01	0.05	-0.08
D05	-0.12	0.18	-0.39	0.27	-0.42	0.29	0.04	-0.48	0.15	-0.50	0.17	0.05	0.18	-0.22	0.21	0.23	0.23	-0.12	-0.03	-0.15	-0.03	-0.10	0.16	-0.32	0.22	-0.34	0.22
D06	0.15	0.07	-0.11	-0.04	-0.01	0.15	0.11	-0.17	0.53	-0.25	0.66	0.23	0.19	0.00	0.02	0.30	0.30	-0.23	0.26	-0.33	0.41	0.21	0.04	0.01	-0.06	0.16	0.06
D07	0.02	0.11	-0.32	0.16	-0.28	0.25	0.07	-0.45	0.22	-0.50	0.30	0.18	0.17	-0.13	0.14	0.28	0.28	-0.12	0.04	-0.19	0.09	0.00	0.13	-0.25	0.14	-0.21	0.20
D08	0.06	-0.13	0.13	-0.02	0.17	-0.12	-0.04	0.14	-0.10	0.16	-0.11	0.03	-0.14	0.08	0.02	-0.08	-0.08	0.13	-0.11	0.16	-0.14	0.04	-0.10	0.09	0.00	0.10	-0.06
Slope	-0.06	-0.17	0.27	-0.11	0.21	-0.31	0.13	0.23	-0.12	0.23	-0.12	-0.16	-0.17	0.21	-0.10	-0.22	-0.22	0.19	-0.14	0.25	-0.19	-0.12	-0.12	0.20	-0.10	0.10	-0.21
WS-Savannah																											
Bio1	-0.36	0.32	-0.34	0.34	-0.39	0.35	-0.47	-0.43	0.14	-0.43	0.04	-0.22	0.30	-0.28	0.30	-0.32	0.32	-0.25	0.09	-0.34	-0.02	-0.33	0.27	-0.32	0.32	-0.37	0.31
Bio5	-0.58	0.44	-0.57	0.45	-0.64	0.48	-0.66	-0.71	0.37	-0.70	0.37	-0.32	0.42	-0.47	0.45	-0.49	0.46	-0.59	0.29	-0.69	0.18	-0.44	0.40	-0.48	0.43	-0.49	0.43
Bio6	0.38	-0.20	0.29	-0.18	0.37	-0.20	0.28	0.43	-0.33	0.44	-0.47	0.20	-0.20	0.24	-0.22	0.26	-0.21	0.50	-0.27	0.51	-0.26	0.22	-0.21	0.21	-0.18	0.22	-0.19
Bio12	**0.78**	-0.59	**0.75**	-0.60	**0.83**	-0.62	**0.77**	**0.89**	-0.40	**0.89**	-0.38	0.42	-0.54	0.63	-0.60	0.63	-0.58	0.66	-0.43	**0.76**	-0.32	0.59	-0.55	0.69	-0.57	0.69	-0.56
Bio13	0.67	-0.62	0.59	-0.59	0.69	-0.65	0.67	**0.77**	-0.34	**0.76**	-0.23	0.42	-0.57	0.53	-0.58	0.58	-0.60	0.39	-0.32	0.49	-0.20	0.56	-0.57	0.60	-0.57	0.66	-0.61
Bio14	0.30	-0.13	0.43	-0.17	0.40	-0.17	0.35	0.40	-0.23	0.40	-0.32	0.11	-0.13	0.34	-0.19	0.26	-0.17	0.55	-0.18	0.61	-0.15	0.17	-0.12	0.31	-0.15	0.22	-0.13
D01	0.49	-0.18	0.50	-0.25	0.54	-0.20	0.38	0.45	-0.15	0.45	-0.23	0.26	-0.15	0.40	-0.27	0.39	-0.17	0.49	-0.28	0.53	-0.27	0.36	-0.21	0.41	-0.23	0.38	-0.16
D03	-0.69	0.61	-0.55	0.58	-0.68	0.63	-0.62	-0.71	0.37	-0.71	0.27	-0.54	0.54	-0.54	0.57	-0.65	0.57	-0.53	0.34	-0.61	0.24	-0.56	0.56	-0.55	0.58	-0.64	0.60
D05	-0.60	0.61	-0.42	0.53	-0.57	0.63	-0.59	-0.64	0.40	-0.63	0.26	-0.52	0.58	-0.44	0.52	-0.59	0.61	-0.39	0.24	-0.48	0.08	-0.51	0.54	-0.46	0.53	-0.58	0.62
D06	0.69	-0.41	0.66	-0.47	0.74	-0.44	0.58	0.68	-0.30	0.69	-0.34	0.43	-0.36	0.58	-0.49	0.59	-0.40	0.58	-0.37	0.66	-0.32	0.54	-0.41	0.59	-0.45	0.59	-0.40
D07	0.43	-0.33	0.41	-0.34	0.46	-0.35	0.43	0.42	-0.22	0.42	-0.20	0.32	-0.31	0.37	-0.34	0.41	-0.33	0.30	-0.07	0.38	0.02	0.39	-0.30	0.40	-0.33	0.44	-0.32
D08	**0.75**	-0.48	0.69	-0.53	**0.79**	-0.51	0.68	**0.81**	-0.33	**0.81**	-0.36	0.45	-0.43	0.58	-0.53	0.62	-0.46	0.69	-0.38	**0.78**	-0.30	0.59	-0.46	0.62	-0.50	0.64	-0.45
D09	0.71	-0.52	**0.77**	-0.56	**0.80**	-0.57	0.74	**0.83**	-0.38	**0.83**	-0.40	0.36	-0.49	0.66	-0.58	0.61	-0.54	0.62	-0.44	0.73	-0.35	0.52	-0.51	0.69	-0.54	0.63	-0.52
Slope	0.21	-0.11	0.21	-0.13	0.22	-0.10	0.13	0.19	-0.02	0.19	-0.04	0.12	-0.07	0.17	-0.13	0.16	-0.07	0.19	-0.16	0.19	-0.17	0.15	-0.12	0.19	-0.12	0.17	-0.08

TABLE B.7 - ***Functional diversity in each dryland. Species taxonomic information, functional group assignment codes (see Table 4.2 for definition of codes) and biological traits considered for determining functional groups. Thermoregulation is coded as ECTO (ectothermic) or ENDO (endothermic); Water refers to water dependency in some stage of life cycle and is coded as YES or NO; Reproduction is coded as oviparity, viviparity or ovoviviparity; Fecundity is coded in number of eggs, using categories: 1, <5, 5- 10; 10-15; 15-20; 20-30; 30-50; 50-100; >100; and not available (NA); Body Size (cm) is coded using categories: <30; 30-100; >100; and EOO refers to the IUCN extent of occurrence (millions of km2), coded using categories: <0.1; >0.1; >0.25; >0.5; >0.75; >1; >2.5; >5; >7.5; >10; >25; >50; >75.***

Australien

Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Ecto_SmBS	Reptilia	*Austrotyphlops centralis*	ECTO	NO	Oviparity	<30	<30	<0.1
	Reptilia	*Austrotyphlops diversus*	ECTO	NO	Oviparity	<30	<30	>1
	Reptilia	*Austrotyphlops grypus*	ECTO	NO	Oviparity	<30	<30	>2.5
	Reptilia	*Austrotyphlops proximus*	ECTO	NO	Oviparity	<30	<30	>0.25
	Reptilia	*Carlia munda*	ECTO	NO	Oviparity	NA	<30	>2.5
	Reptilia	*Cryptoblepharus boutonii*	ECTO	NO	Oviparity	NA	<30	<0.1
	Reptilia	*Ctenophorus caudicinctus*	ECTO	NO	Oviparity	<10	<30	>2.5
	Reptilia	*Ctenophorus clayi*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Ctenophorus cristatus*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Ctenophorus decresii*	ECTO	NO	Oviparity	<10	<30	>0.1
	Reptilia	*Ctenophorus fionni*	ECTO	NO	Oviparity	<10	<30	>0.1
	Reptilia	*Ctenophorus gibba*	ECTO	NO	Oviparity	<10	<30	<0.1
	Reptilia	*Ctenophorus maculosus*	ECTO	NO	Oviparity	<10	<30	<0.1
	Reptilia	*Ctenophorus rufescens*	ECTO	NO	Oviparity	<10	<30	<0.1

TABLE B.7 - *Continued.*

Australien

Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km²)
Ecto_SmBS	Reptilia	*Ctenophorus tjantjalka*	ECTO	NO	Oviparity	<10	<30	<0.1
	Reptilia	*Ctenophorus vadnappa*	ECTO	NO	Oviparity	<10	<30	<0.1
	Reptilia	*Ctenotus alacer*	ECTO	NO	Oviparity	<10	<30	<0.1
	Reptilia	*Ctenotus ariadnae*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Ctenotus brachyonyx*	ECTO	NO	Oviparity	<10	<30	>0.25
	Reptilia	*Ctenotus calurus*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Ctenotus dux*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Ctenotus greeri*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Ctenotus saxatilis*	ECTO	NO	Oviparity	<10	<30	>2.5
	Reptilia	*Ctenotus strauchii*	ECTO	NO	Oviparity	<10	<30	>2.5
	Reptilia	*Egernia formosa*	ECTO	NO	Viviparity	<10	<30	>0.75
	Reptilia	*Lophognathus gilberti*	ECTO	NO	Oviparity	<10	<30	>0.25
	Reptilia	*Notoscincus ornatus*	ECTO	NO	Oviparity	NA	<30	>0.75
	Reptilia	*Proablepharus kinghorni*	ECTO	NO	Oviparity	NA	<30	>0.75
	Reptilia	*Ramphotyphlops braminus*	ECTO	NO	Oviparity	<10	<30	>0.25
	Reptilia	*Tympanocryptis intima*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Tympanocryptis tetraporophora*	ECTO	NO	Oviparity	<10	<30	>2.5
MeFEC	Mammalia	*Chaeropus ecaudatus*	ENDO	NO	Viviparity	<5	<30	>5
	Reptilia	*Cyclodomorphus branchialis*	ECTO	NO	Viviparity	<5	<30	>0.1
	Mammalia	*Dasycercus blythi*	ENDO	NO	Viviparity	<5	<30	>1
	Reptilia	*Diplodactylus furcosus*	ECTO	NO	Oviparity	<5	<30	>0.1

TABLE B.7 - *Continued.*

Australien

Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km²)
MeFEC	Reptilia	*Diplodactylus granariensis*	ECTO	NO	Oviparity	<5	<30	>0.1
	Reptilia	*Hemiergis decresiensis*	ECTO	NO	Viviparity	<5	<30	>1
	Reptilia	*Hemiergis millewae*	ECTO	NO	Viviparity	<5	<30	>0.25
	Reptilia	*Hemiergis peronii*	ECTO	NO	Viviparity	<5	<30	>0.5
	Mammalia	*Lasiorhinus latifrons*	ENDO	NO	Viviparity	<5	30-100	<0.1
	Mammalia	*Leggadina forresti*	ENDO	NO	Viviparity	<5	<30	>1
	Mammalia	*Leporillus apicalis*	ENDO	NO	Viviparity	<5	<30	>0.5
	Reptilia	*Lerista edwardsae*	ECTO	NO	Oviparity	<5	<30	>0.1
	Reptilia	*Lerista terdigitata*	ECTO	NO	Oviparity	<5	<30	>0.1
	Reptilia	*Liopholis margaretae*	ECTO	NO	Viviparity	<5	<30	>0.5
	Reptilia	*Liopholis multiscutata*	ECTO	NO	Viviparity	<5	<30	>0.75
	Reptilia	*Liopholis striata*	ECTO	NO	Viviparity	<5	<30	>1
	Reptilia	*Liopholis whitii*	ECTO	NO	Viviparity	<5	<30	>0.75
	Mammalia	*Macrotis lagotis*	ENDO	NO	Viviparity	<5	30-100	>1
	Mammalia	*Notomys alexis*	ENDO	NO	Viviparity	<5	<30	>2.5
	Mammalia	*Notomys amplus*	ENDO	NO	Viviparity	<5	<30	>0.1
	Mammalia	*Notomys fuscus*	ENDO	NO	Viviparity	<5	<30	>0.1
	Mammalia	*Notomys longicaudatus*	ENDO	NO	Viviparity	<5	<30	>0.1
	Mammalia	*Notoryctes typhlops*	ENDO	NO	Viviparity	<5	<30	>1
	Mammalia	*Pseudomys australis*	ENDO	NO	Viviparity	<5	<30	>0.1
	Mammalia	*Pseudomys bolami*	ENDO	NO	Viviparity	<5	<30	>0.75

TABLE B.7 - *Continued.*

Australien

Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km²)
MeFEC	Mammalia	*Pseudomys desertor*	ENDO	NO	Viviparity	<5	<30	>5
	Mammalia	*Pseudomys gouldii*	ENDO	NO	Viviparity	<5	<30	>0.5
	Mammalia	*Pseudomys hermannsburgensis*	ENDO	NO	Viviparity	<5	<30	>2.5
	Reptilia	*Suta punctata*	ECTO	NO	Viviparity	<5	30-100	>2.5
	Reptilia	*Tiliqua occipitalis*	ECTO	NO	Viviparity	<5	30-100	>2.5
	Reptilia	*Tiliqua rugosa*	ECTO	NO	Viviparity	<5	30-100	>2.5
	Mammalia	*Zyzomys pedunculatus*	ENDO	NO	Viviparity	<5	<30	<0.1
Ecto_MeEOO	Reptilia	*Ctenophorus fordi*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Ctenophorus pictus*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Ctenophorus reticulatus*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Ctenotus atlas*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Ctenotus grandis*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Ctenotus leae*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Ctenotus piankai*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Ctenotus quattuordecimlineatus*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Ctenotus regius*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Ctenotus taeniolatus*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Diporiphora lalliae*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Diporiphora nobbi*	ECTO	NO	Oviparity	<10	<30	>1
SmBS	Reptilia	*Ctenotus hanloni*	ECTO	NO	Oviparity	<10	<30	>0.5
	Reptilia	*Ctenotus nasutus*	ECTO	NO	Oviparity	<10	<30	>0.5

TABLE B.7 - *Continued.*

Australien

Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km²)
SmBS	Reptilia	*Ctenotus olympicus*	ECTO	NO	Oviparity	<10	<30	>0.5
	Reptilia	*Ctenotus septenarius*	ECTO	NO	Oviparity	<10	<30	>0.5
	Reptilia	*Egernia stokesii*	ECTO	NO	Viviparity	<10	<30	>1
	Reptilia	*Egernia striolata*	ECTO	NO	Viviparity	<10	<30	>1
	Reptilia	*Eulamprus quoyii*	ECTO	NO	Viviparity	<10	<30	>1
	Reptilia	*Lampropholis guichenoti*	ECTO	NO	Oviparity	<10	<30	>0.5
	Mammalia	*Ningaui ridei*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Planigale gilesi*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Planigale ingrami*	ENDO	NO	Viviparity	<10	<30	>0.5
	Mammalia	*Planigale tenuirostris*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Pseudantechinus macdonellensis*	ENDO	NO	Viviparity	<10	<30	>0.75
	Mammalia	*Sminthopsis dolichura*	ENDO	NO	Viviparity	<10	<30	>0.5
	Mammalia	*Sminthopsis hirtipes*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Sminthopsis murina*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Sminthopsis ooldea*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Sminthopsis psammophila*	ENDO	NO	Viviparity	<10	<30	<0.1
	Mammalia	*Sminthopsis youngsoni*	ENDO	NO	Viviparity	<10	<30	>1
Ecto_MeFEC	Reptilia	*Amalosia rhombifer*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Carlia triacantha*	ECTO	NO	Oviparity	NA	<30	>1
	Reptilia	*Christinus marmoratus*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Delma australis*	ECTO	NO	Oviparity	<5	<30	>1

TABLE B.7 - *Continued.*

Australien

Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km²)
Ecto_MeFEC	Reptilia	*Diplodactylus tessellatus*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Diplodactylus vittatus*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Lerista aericeps*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Lerista labialis*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Lerista punctatovittata*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Lucasium damaeum*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Nephrurus laevissimus*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Proablepharus reginae*	ECTO	NO	Oviparity	NA	<30	>1
	Reptilia	*Pygopus lepidopodus*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Pygopus schraderi*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Strophurus intermedius*	ECTO	NO	Oviparity	<5	<30	>1
Ecto_SmEOO	Reptilia	*Aprasia inaurita*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Aprasia pseudopulchella*	ECTO	NO	Oviparity	<5	<30	<0.1
	Reptilia	*Crenadactylus ocellatus*	ECTO	NO	Oviparity	<5	<30	>2.5
	Reptilia	*Delma borea*	ECTO	NO	Oviparity	<5	<30	>2.5
	Reptilia	*Delma butleri*	ECTO	NO	Oviparity	<5	<30	>2.5
	Reptilia	*Delma haroldi*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Delma molleri*	ECTO	NO	Oviparity	<5	<30	<0.1
	Reptilia	*Diplodactylus galeatus*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Gehyra lazelli*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Gehyra montium*	ECTO	NO	Oviparity	<5	<30	>0.5

TABLE B.7 - *Continued.*

Australien

Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km²)
Ecto_SmEOO	Reptilia	*Heteronotia spelea*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Lerista bougainvillii*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Lerista desertorum*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Lerista dorsalis*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Lerista frosti*	ECTO	NO	Oviparity	<5	<30	<0.1
	Reptilia	*Lerista orientalis*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Lerista picturata*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Lucasium byrnei*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Lucasium steindachneri*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Morethia adelaidensis*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Morethia obscura*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Morethia taeniopleura*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Nephrurus amyae*	ECTO	NO	Oviparity	<5	<30	<0.1
	Reptilia	*Nephrurus deleani*	ECTO	NO	Oviparity	<5	<30	<0.1
	Reptilia	*Nephrurus stellatus*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Ophidiocephalus taeniatus*	ECTO	NO	Oviparity	<5	<30	<0.1
	Reptilia	*Simoselaps anomalus*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Strophurus jeanae*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Strophurus williamsi*	ECTO	NO	Oviparity	<5	<30	>0.75
LgBS	Reptilia	*Acanthophis antarcticus*	ECTO	NO	Viviparity	<20	30-100	>2.5
	Reptilia	*Acanthophis pyrrhus*	ECTO	NO	Viviparity	<20	30-100	>2.5

TABLE B.7 - *Continued.*

Australien								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km²)
LgBS	Reptilia	*Brachyurophis australis*	ECTO	NO	Oviparity	<5	30-100	>1
	Reptilia	*Brachyurophis incinctus*	ECTO	NO	Oviparity	<5	30-100	>0.5
	Mammalia	*Canis lupus dingo*	ENDO	NO	Viviparity	<10	>100	>7.5
	Reptilia	*Echiopsis curta*	ECTO	NO	Ovoviparity	<20	30-100	>0.5
	Reptilia	*Emydura macquarii*	ECTO	NO	Oviparity	<20	30-100	>2.5
	Reptilia	*Furina diadema*	ECTO	NO	Oviparity	<10	30-100	>1
	Mammalia	*Macropus fuliginosus*	ENDO	NO	Viviparity	1	>100	>1
	Mammalia	*Macropus giganteus*	ENDO	NO	Viviparity	1	>100	>2.5
	Mammalia	*Macropus robustus*	ENDO	NO	Viviparity	1	>100	>5
	Reptilia	*Morelia spilota*	ECTO	NO	Oviparity	<50	>100	>7.5
	Reptilia	*Notechis scutatus*	ECTO	NO	Viviparity	<30	>100	>0.1
	Reptilia	*Oxyuranus microlepidotus*	ECTO	NO	Oviparity	<20	>100	>0.1
	Reptilia	*Parasuta nigriceps*	ECTO	NO	Viviparity	<10	30-100	>0.5
	Reptilia	*Parasuta spectabilis*	ECTO	NO	Viviparity	<10	30-100	>0.25
	Mammalia	*Petrogale lateralis*	ENDO	NO	Viviparity	1	30-100	>0.1
	Mammalia	*Petrogale xanthopus*	ENDO	NO	Viviparity	1	30-100	<0.1
	Reptilia	*Pogona mitchelli*	ECTO	NO	Oviparity	<20	30-100	>1
	Reptilia	*Pseudechis porphyriacus*	ECTO	NO	Ovoviparityv	<20	>100	>0.75
	Reptilia	*Pseudonaja aspidorhyncha*	ECTO	NO	Oviparity	<20	>100	>1
	Reptilia	*Pseudonaja inframacula*	ECTO	NO	Oviparity	<20	>100	>0.1
	Reptilia	*Pseudonaja mengdeni*	ECTO	NO	Oviparity	<20	>100	>2.5

TABLE B.7 - *Continued.*

Australien

Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km²)
LgBS	Reptilia	*Pseudonaja textilis*	ECTO	NO	Oviparity	<20	>100	>2.5
	Reptilia	*Ramphotyphlops bicolor*	ECTO	NO	Oviparity	<10	30-100	>1
	Mammalia	*Trichosurus vulpecula*	ENDO	NO	Viviparity	1	30-100	>2.5
	Reptilia	*Varanus giganteus*	ECTO	NO	Oviparity	<10	>100	>1
	Reptilia	*Varanus gilleni*	ECTO	NO	Oviparity	<5	30-100	>1
	Reptilia	*Varanus varius*	ECTO	NO	Oviparity	<10	>100	>1
	Reptilia	*Vermicella annulata*	ECTO	NO	Oviparity	<10	30-100	>2.5
Water	Amphibia	*Crinia riparia*	ECTO	YES	Oviparity	NA	<30	<0.1
	Amphibia	*Limnodynastes peronii*	ECTO	YES	Oviparity	>100	<30	>0.75
	Amphibia	*Limnodynastes tasmaniensis*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Litoria adelaidensis*	ECTO	YES	Oviparity	>100	<30	>0.1
	Amphibia	*Litoria australis*	ECTO	YES	Oviparity	>100	<30	>1
	Amphibia	*Litoria gilleni*	ECTO	YES	Oviparity	>100	<30	<0.1
	Amphibia	*Litoria maini*	ECTO	YES	Oviparity	>100	<30	>1
	Amphibia	*Neobatrachus centralis*	ECTO	YES	Oviparity	>100	<30	>0.5
	Amphibia	*Neobatrachus kunapalari*	ECTO	YES	Oviparity	>100	<30	>0.25
	Amphibia	*Neobatrachus pictus*	ECTO	YES	Oviparity	>100	<30	>0.25
	Amphibia	*Platyplectrum ornatum*	ECTO	YES	Oviparity	>100	<30	>1
	Amphibia	*Platyplectrum spenceri*	ECTO	YES	Oviparity	>100	<30	>1

TABLE B.7 - *Continued.*

Caatinga								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Endo_MeFEC	Mammalia	*Cerdocyon thous*	ENDO	NO	Viviparity	<5	30-100	>7.5
	Mammalia	*Conepatus semistriatus*	ENDO	NO	Viviparity	<5	30-100	>1
	Mammalia	*Euphractus sexcinctus*	ENDO	NO	Viviparity	<5	30-100	>7.5
	Mammalia	*Panthera onca*	ENDO	NO	Viviparity	<5	>100	>7.5
	Mammalia	*Puma concolor*	ENDO	NO	Viviparity	<5	>100	>25
	Mammalia	*Tayassu pecari*	ENDO	NO	Viviparity	<5	>100	>10
SmBS	Mammalia	*Callithrix jacchus*	ENDO	NO	Viviparity	<5	<30	>0.75
	Mammalia	*Calomys callosus*	ENDO	NO	Viviparity	<5	<30	>2.5
	Mammalia	*Cerradomys subflavus*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Didelphis albiventris*	ENDO	NO	Viviparity	<15	<30	>5
	Mammalia	*Gracilinanus agilis*	ENDO	NO	Viviparity	<15	<30	>2.5
	Mammalia	*Monodelphis domestica*	ENDO	NO	Viviparity	<15	<30	>2.5
	Mammalia	*Necromys lasiurus*	ENDO	NO	Viviparity	<5	<30	>10
	Mammalia	*Thrichomys apereoides*	ENDO	NO	Viviparity	<5	<30	>1
	Reptilia	*Tropidurus hispidus*	ECTO	NO	Oviparity	<5	<30	>2.5
Endo_MeBS	Mammalia	*Cuniculus paca*	ENDO	NO	Viviparity	<5	30-100	>10
	Mammalia	*Leopardus pardalis*	ENDO	NO	Viviparity	<5	30-100	>10
	Mammalia	*Leopardus tigrinus*	ENDO	NO	Viviparity	<5	30-100	>10
	Mammalia	*Pecari tajacu*	ENDO	NO	Viviparity	<5	30-100	>10
	Mammalia	*Procyon cancrivorus*	ENDO	NO	Viviparity	<5	30-100	>10
Water_SmEOO	Amphibia	*Hypsiboas albomarginatus*	ECTO	YES	Oviparity	>100	<30	>0.5

TABLE B.7 - *Continued.*

Caatinga								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Water_SmEOO	Amphibia	*Hypsiboas crepitans*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Hypsiboas faber*	ECTO	YES	Oviparity	>100	<30	>1
	Amphibia	*Leptodactylus ocellatus*	ECTO	YES	Oviparity	>100	<30	>5
	Amphibia	*Physalaemus cuvieri*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Pseudopaludicola mystacalis*	ECTO	YES	Oviparity	>100	<30	>0.25
	Amphibia	*Rhinella crucifer*	ECTO	YES	Oviparity	>100	<30	>0.5
	Amphibia	*Rhinella schneideri*	ECTO	YES	Oviparity	>100	<30	>5
	Amphibia	*Scinax fuscovarius*	ECTO	YES	Oviparity	>100	<30	>5
Endo_LoFEC	Mammalia	*Alouatta caraya*	ENDO	NO	Viviparity	1	30-100	>2.5
	Mammalia	*Coendou prehensilis*	ENDO	NO	Viviparity	1	30-100	>10
	Mammalia	*Mazama gouazoubira*	ENDO	NO	Viviparity	1	>100	>5
	Mammalia	*Ozotoceros bezoarticus*	ENDO	NO	Viviparity	1	>100	>0.5
Ecto_MeBS	Amphibia	*Siphonops annulatus*	ECTO	YES	Oviparity	<20	30-100	>10
	Reptilia	*Amphisbaena alba*	ECTO	NO	Oviparity	<20	30-100	>10
	Reptilia	*Liophis poecilogyrus*	ECTO	NO	Oviparity	<10	30-100	>7.5
	Reptilia	*Oxyrhopus trigeminus*	ECTO	NO	Oviparity	<10	30-100	>0.5
	Reptilia	*Salvator rufescens*	ECTO	NO	Oviparity	<30	30-100	>0.25
Water_LgEOO	Amphibia	*Elachistocleis ovalis*	ECTO	YES	Oviparity	>100	<30	>10
	Amphibia	*Leptodactylus fuscus*	ECTO	YES	Oviparity	>100	<30	>10
	Amphibia	*Rhinella granulosus*	ECTO	YES	Oviparity	>100	<30	>10
	Amphibia	*Rhinella marinus*	ECTO	YES	Oviparity	>100	<30	>10

TABLE B.7 - *Continued.*

Caatinga								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Ecto_LgEOO	Reptilia	*Ameiva ameiva*	ECTO	NO	Oviparity	<10	<30	>7.5
	Reptilia	*Crotalus durissus*	ECTO	NO	Viviparity	<30	>100	>7.5
	Reptilia	*Iguana iguana*	ECTO	NO	Oviparity	<50	>100	>10
	Reptilia	*Oxybelis aeneus*	ECTO	NO	Oviparity	<5	>100	>10
	Reptilia	*Philodryas olfersii*	ECTO	NO	Oviparity	<10	>100	>7.5
	Reptilia	*Polychrus acutirostris*	ECTO	NO	Oviparity	<30	<30	>0.75
	Reptilia	*Tropidurus torquatus*	ECTO	NO	Oviparity	<5	<30	>7.5
	Reptilia	*Xenodon merremi*	ECTO	NO	Oviparity	<30	>100	>5
Water_MeEOO	Amphibia	*Dendropsophus nanus*	ECTO	YES	Oviparity	>100	<30	>7.5
	Amphibia	*Hypsiboas raniceps*	ECTO	YES	Oviparity	>100	<30	>7.5
	Amphibia	*Lithobates palmipes*	ECTO	YES	Oviparity	>100	<30	>7.5
	Amphibia	*Scinax ruber*	ECTO	YES	Oviparity	>100	<30	>7.5

TABLE B.7 - *Continued.*

SW Africa

Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
SmBS	Reptilia	*Acanthocercus atricollis*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Agama aculeata*	ECTO	NO	Oviparity	<10	<30	>7.5
	Reptilia	*Agama anchietae*	ECTO	NO	Oviparity	<10	<30	>7.5
	Reptilia	*Agama atra*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Agama hispida*	ECTO	NO	Oviparity	<10	<30	>0.1
	Reptilia	*Chamaeleo dilepis*	ECTO	NO	Oviparity	<50	<30	>5
	Reptilia	*Chamaeleo namaquensis*	ECTO	NO	Oviparity	<20	<30	>0.5
	Mammalia	*Dendromus melanotis*	ENDO	NO	Viviparity	<10	<30	>2.5
	Reptilia	*Leptotyphlops scutifrons*	ECTO	NO	Oviparity	<10	<30	>2.5
	Mammalia	*Malacothrix typica*	ENDO	NO	Viviparity	<10	<30	>1
	Reptilia	*Meroles ctenodactylus*	ECTO	NO	Oviparity	<6	<30	>0.1
	Reptilia	*Meroles cuneirostris*	ECTO	NO	Oviparity	<7	<30	>0.1
	Reptilia	*Meroles knoxii*	ECTO	NO	Oviparity	<8	<30	>0.1
	Reptilia	*Meroles reticulatus*	ECTO	NO	Oviparity	<9	<30	<0.1
	Reptilia	*Meroles suborbitalis*	ECTO	NO	Oviparity	<10	<30	>0.1
	Mammalia	*Mus indutus*	ENDO	NO	Viviparity	<10	<30	>1
	Reptilia	*Nucras intertexta*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Nucras ornata*	ECTO	NO	Oviparity	<10	<30	>2.5
	Reptilia	*Nucras tessellata*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Pedioplanis breviceps*	ECTO	NO	Oviparity	<10	<30	<0.1
	Reptilia	*Pedioplanis gaerdesi*	ECTO	NO	Oviparity	<10	<30	<0.1

TABLE B.7 - *Continued.*

SW Africa								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
	Reptilia	*Pedioplanis inornata*	ECTO	NO	Oviparity	<10	<30	>0.5
	Reptilia	*Pedioplanis lineoocellata*	ECTO	NO	Oviparity	<10	<30	>0.5
	Reptilia	*Pedioplanis namaquensis*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Pedioplanis undata*	ECTO	NO	Oviparity	<10	<30	>0.5
	Mammalia	*Saccostomus campestris*	ENDO	NO	Viviparity	<10	<30	>5
	Reptilia	*Trachylepis acutilabris*	ECTO	NO	Viviparity	<10	<30	>1
	Reptilia	*Trachylepis binotata*	ECTO	NO	Viviparity	<10	<30	>0.25
	Reptilia	*Trachylepis capensis*	ECTO	NO	Viviparity	<10	<30	>1
	Reptilia	*Trachylepis hoeschi*	ECTO	NO	Viviparity	<10	<30	>0.25
	Reptilia	*Trachylepis occidentalis*	ECTO	NO	Viviparity	<10	<30	>0.5
	Reptilia	*Trachylepis spilogaster*	ECTO	NO	Viviparity	<10	<30	>0.5
	Reptilia	*Trachylepis striata*	ECTO	NO	Viviparity	<10	<30	>5
	Reptilia	*Trachylepis sulcata*	ECTO	NO	Viviparity	<10	<30	>0.5
	Reptilia	*Trachylepis varia*	ECTO	NO	Viviparity	<10	<30	>7.5
	Reptilia	*Trachylepis variegata*	ECTO	NO	Viviparity	<10	<30	>2.5
Ecto_SmBS	Reptilia	*Acontias gracilicauda*	ECTO	NO	Viviparity	<5	<30	>0.25
	Reptilia	*Chondrodactylus fitzsimonsi*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Cordylosaurus subtessellatus*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Karusasaurus jordani*	ECTO	NO	Ovoviviparity	<5	<30	>0.25
	Reptilia	*Karusasaurus polyzonus*	ECTO	NO	Ovoviviparity	<5	<30	>0.25
	Reptilia	*Microacontias lineatus*	ECTO	NO	Viviparity	<5	<30	>0.25

TABLE B.7 - *Continued.*

SW Africa								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Ecto_SmBS	Reptilia	*Pachydactylus maculatus*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Pachydactylus rangei*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Pachydactylus serval*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Pachydactylus vanzyli*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Platysaurus capensis*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Psammobates tentorius*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Pseudocordylus microlepidotus*	ECTO	NO	Ovoviviparity	<5	<30	>0.25
	Reptilia	*Rhoptropus afer*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Rhoptropus barnardi*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Typhlacontias brevipes*	ECTO	NO	Viviparity	<5	<30	>0.25
	Reptilia	*Typhlacontias punctatissimus*	ECTO	NO	Viviparity	<5	<30	>0.25
Ecto_MeEOO	Reptilia	*Aspidelaps lubricus*	ECTO	NO	Oviparity	<10	30-100	>1
	Reptilia	*Aspidelaps scutatus*	ECTO	NO	Oviparity	<10	30-100	>1
	Reptilia	*Psammophis notostictus*	ECTO	NO	Oviparity	<10	30-100	>1
	Reptilia	*Psammophis subtaeniatus*	ECTO	NO	Oviparity	<10	30-100	>1
Ecto_MeBS	Reptilia	*Bitis caudalis*	ECTO	NO	Viviparity	<30	30-100	>2.5
	Reptilia	*Boaedon fuliginosus*	ECTO	NO	Oviparity	<15	30-100	>10
	Reptilia	*Chamaesaura anguina*	ECTO	NO	Ovoviviparity	<20	30-100	>5
	Reptilia	*Dasypeltis scabra*	ECTO	NO	Oviparity	<20	30-100	>10
	Reptilia	*Dipsina multimaculata*	ECTO	NO	Oviparity	<5	30-100	>0.75
	Reptilia	*Gerrhosaurus nigrolineatus*	ECTO	NO	Oviparity	<5	30-100	>7.5

TABLE B.7 - *Continued.*

SW Africa								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Ecto_MeBS	Reptilia	*Gerrhosaurus validus*	ECTO	NO	Oviparity	<5	30-100	>1
	Reptilia	*Lamprophis guttatus*	ECTO	NO	Oviparity	<5	30-100	>0.5
	Reptilia	*Megatyphlops schlegelii*	ECTO	NO	Oviparity	<50	30-100	>7.5
	Reptilia	*Philothamnus semivariegatus*	ECTO	NO	Oviparity	<10	30-100	>7.5
	Reptilia	*Prosymna frontalis*	ECTO	NO	Oviparity	<5	30-100	>0.5
	Reptilia	*Psammophis leightoni*	ECTO	NO	Oviparity	<10	30-100	<0.1
	Reptilia	*Psammophis trigrammus*	ECTO	NO	Oviparity	<10	30-100	>0.5
	Reptilia	*Psammophylax rhombeatus*	ECTO	NO	Oviparity	<30	30-100	>1
	Reptilia	*Psammophylax tritaeniatus*	ECTO	NO	Oviparity	<30	30-100	>2.5
	Reptilia	*Pythonodipsas carinata*	ECTO	NO	Oviparity	NA	30-100	>0.5
	Reptilia	*Rhinotyphlops lalandei*	ECTO	NO	Oviparity	<5	30-100	>2.5
	Reptilia	*Stigmochelys pardalis*	ECTO	NO	Oviparity	<20	30-100	>7.5
	Reptilia	*Telescopus beetzi*	ECTO	NO	Oviparity	<20	30-100	>0.25
	Reptilia	*Telescopus semiannulatus*	ECTO	NO	Oviparity	<20	30-100	>5
	Reptilia	*Xenocalamus bicolor*	ECTO	NO	Oviparity	<5	30-100	>2.5
Ecto_MeFEC	Reptilia	*Acontias meleagris*	ECTO	NO	Viviparity	<5	<30	>0.5
	Reptilia	*Acontias percivali*	ECTO	NO	Viviparity	<5	<30	>0.75
	Reptilia	*Chondrodactylus angulifer*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Chondrodactylus bibronii*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Chondrodactylus turneri*	ECTO	NO	Oviparity	<5	<30	>5
	Reptilia	*Cordylus cordylus*	ECTO	NO	Ovoviviparity	<5	<30	>0.75

TABLE B.7 - *Continued.*

SW Africa								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Ecto_MeFEC	Reptilia	*Goggia lineata*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Heliobolus lugubris*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Lygodactylus bradfieldi*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Lygodactylus capensis*	ECTO	NO	Oviparity	<5	<30	>5
	Reptilia	*Lygodactylus lawrencei*	ECTO	NO	Oviparity	<5	<30	>0.1
	Reptilia	*Lygosoma sundevalli*	ECTO	NO	Oviparity	<5	<30	>5
	Reptilia	*Meroles anchietae*	ECTO	NO	Oviparity	<5	<30	>0.1
	Reptilia	*Narudasia festiva*	ECTO	NO	Oviparity	<5	<30	<0.1
	Reptilia	*Pachydactylus bicolor*	ECTO	NO	Oviparity	<5	<30	<0.1
	Reptilia	*Pachydactylus carinatus*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Pachydactylus haackei*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Pachydactylus laevigatus*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Pachydactylus mariquensis*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Pachydactylus montanus*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Pachydactylus punctatus*	ECTO	NO	Oviparity	<5	<30	>2.5
	Reptilia	*Pachydactylus purcelli*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Pachydactylus rugosus*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Pachydactylus scherzi*	ECTO	NO	Oviparity	<5	<30	<0.1
	Reptilia	*Pachydactylus scutatus*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Pachydactylus weberi*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Panaspis wahlbergii*	ECTO	NO	Oviparity	<5	<30	>5

TABLE B.7 - *Continued.*

SW Africa								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Ecto_MeFEC	Reptilia	*Ptenopus garrulus*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Rhoptropus biporosus*	ECTO	NO	Oviparity	<5	<30	>0.1
	Reptilia	*Rhoptropus boultoni*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Rhoptropus bradfieldi*	ECTO	NO	Oviparity	<5	<30	>0.1
	Reptilia	*Smaug giganteus*	ECTO	NO	Viviparity	<5	<30	>0.1
	Reptilia	*Typhlosaurus lineatus*	ECTO	NO	Viviparity	<5	<30	>0.75
Ecto_LgBS	Reptilia	*Bitis arietans*	ECTO	NO	Viviparity	<50	>100	>10
	Reptilia	*Dendroaspis polylepis*	ECTO	NO	Oviparity	<20	>100	>2.5
	Reptilia	*Hemachatus haemachatus*	ECTO	NO	Ovoviviparity	<50	>100	>0.5
	Reptilia	*Lycodonomorphus laevissimus*	ECTO	NO	Oviparity	<20	>100	<0.1
	Reptilia	*Naja nivea*	ECTO	NO	Oviparity	<20	>100	>1
	Reptilia	*Pseudaspis cana*	ECTO	NO	Viviparity	<50	>100	>2.5
	Reptilia	*Thelotornis capensis*	ECTO	NO	Oviparity	<20	>100	>2.5
	Reptilia	*Varanus albigularis*	ECTO	NO	Oviparity	<50	>100	>7.5
Endo_LoFEC	Mammalia	*Alcelaphus buselaphus*	ENDO	NO	Viviparity	1	>100	>5
	Mammalia	*Antidorcas marsupialis*	ENDO	NO	Viviparity	1	>100	>1
	Mammalia	*Chlorocebus pygerythrus*	ENDO	NO	Viviparity	1	30-100	>2.5
	Mammalia	*Connochaetes gnou*	ENDO	NO	Viviparity	1	>100	>0.25
	Mammalia	*Diceros bicornis*	ENDO	NO	Viviparity	1	>100	>7.5
	Mammalia	*Equus quagga*	ENDO	NO	Viviparity	1	>100	>1
	Mammalia	*Giraffa camelopardalis*	ENDO	NO	Viviparity	1	>100	>1

TABLE B.7 - *Continued.*

SW Africa								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Endo_LoFEC	Mammalia	*Hippopotamus amphibius*	ENDO	NO	Viviparity	1	>100	>1
	Mammalia	*Oreotragus oreotragus*	ENDO	NO	Viviparity	1	>100	>5
	Mammalia	*Oryx gazella*	ENDO	NO	Viviparity	1	>100	>1
	Mammalia	*Papio ursinus*	ENDO	NO	Viviparity	1	>100	>2.5
	Mammalia	*Pedetes capensis*	ENDO	NO	Viviparity	1	30-100	>2.5
	Mammalia	*Raphicerus campestris*	ENDO	NO	Viviparity	1	30-100	>2.5
	Mammalia	*Redunca arundinum*	ENDO	NO	Viviparity	1	>100	>2.5
	Mammalia	*Redunca fulvorufula*	ENDO	NO	Viviparity	1	>100	>1
	Mammalia	*Tragelaphus oryx*	ENDO	NO	Viviparity	1	>100	>5
Water	Amphibia	*Amietia angolensis*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Amietia fuscigula*	ECTO	YES	Oviparity	>100	<30	>0.25
	Amphibia	*Amietophrynus gutturalis*	ECTO	YES	Oviparity	>100	<30	>5
	Amphibia	*Amietophrynus rangeri*	ECTO	YES	Oviparity	>100	<30	>0.75
	Amphibia	*Breviceps adspersus*	ECTO	YES	Oviparity	<50	<30	>2.5
	Amphibia	*Cacosternum boettgeri*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Phrynomantis annectens*	ECTO	YES	Oviparity	>100	<30	>0.5
	Amphibia	*Pyxicephalus adspersus*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Tomopterna cryptotis*	ECTO	YES	Oviparity	>100	<30	>10
	Amphibia	*Tomopterna delalandii*	ECTO	YES	Oviparity	>100	<30	>0.25
	Amphibia	*Vandijkophrynus gariepensis*	ECTO	YES	Oviparity	>100	<30	>0.5
	Amphibia	*Xenopus laevis*	ECTO	YES	Oviparity	>100	<30	>5

TABLE B.7 - *Continued.*

SW Africa								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Endo_SmBS	Mammalia	*Aethomys chrysophilus*	ENDO	NO	Viviparity	<5	<30	>2.5
	Mammalia	*Aethomys namaquensis*	ENDO	NO	Viviparity	<5	<30	>2.5
	Mammalia	*Crocidura cyanea*	ENDO	NO	Viviparity	<5	<30	>2.5
	Mammalia	*Cryptomys hottentotus*	ENDO	NO	Viviparity	<5	<30	>0.75
	Mammalia	*Desmodillus auricularis*	ENDO	NO	Viviparity	<5	<30	>1
	Mammalia	*Elephantulus intufi*	ENDO	NO	Viviparity	<5	<30	>1
	Mammalia	*Elephantulus myurus*	ENDO	NO	Viviparity	<5	<30	>1
	Mammalia	*Elephantulus rupestris*	ENDO	NO	Viviparity	<5	<30	>0.5
	Mammalia	*Funisciurus congicus*	ENDO	NO	Viviparity	<5	<30	>1
	Mammalia	*Gerbilliscus brantsii*	ENDO	NO	Viviparity	<5	<30	>1
	Mammalia	*Gerbilliscus leucogaster*	ENDO	NO	Viviparity	<5	<30	>5
	Mammalia	*Gerbillurus paeba*	ENDO	NO	Viviparity	<5	<30	>1
	Mammalia	*Helogale parvula*	ENDO	NO	Viviparity	<5	<30	>5
	Mammalia	*Ictonyx striatus*	ENDO	NO	Viviparity	<5	<30	>10
	Mammalia	*Macroscelides proboscideus*	ENDO	NO	Viviparity	<5	<30	>0.75
	Mammalia	*Myotomys unisulcatus*	ENDO	NO	Viviparity	<5	<30	>0.5
	Mammalia	*Mystromys albicaudatus*	ENDO	NO	Viviparity	<5	<30	>0.5
	Mammalia	*Otomys irroratus*	ENDO	NO	Viviparity	<5	<30	>0.5
	Mammalia	*Parotomys brantsii*	ENDO	NO	Viviparity	<5	<30	>0.75
	Mammalia	*Petromyscus collinus*	ENDO	NO	Viviparity	<5	<30	>0.5
	Mammalia	*Rhabdomys pumilio*	ENDO	NO	Viviparity	<5	<30	>2.5

TABLE B.7 - *Continued.*

SW Africa								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Endo_SmBS	Mammalia	*Steatomys pratensis*	ENDO	NO	Viviparity	<5	<30	>2.5
	Mammalia	*Thallomys nigricauda*	ENDO	NO	Viviparity	<5	<30	>1
Endo_MeFEC	Mammalia	*Acinonyx jubatus*	ENDO	NO	Viviparity	<5	>100	>2.5
	Mammalia	*Canis mesomelas*	ENDO	NO	Viviparity	<10	30-100	>5
	Mammalia	*Caracal caracal*	ENDO	NO	Viviparity	<5	>100	>10
	Mammalia	*Cynictis penicillata*	ENDO	NO	Viviparity	<5	30-100	>2.5
	Mammalia	*Herpestes pulverulentus*	ENDO	NO	Viviparity	<5	30-100	>0.75
	Mammalia	*Hyaena brunnea*	ENDO	NO	Viviparity	<5	>100	>2.5
	Mammalia	*Hystrix africaeaustralis*	ENDO	NO	Viviparity	<5	30-100	>7.5
	Mammalia	*Lepus saxatilis*	ENDO	NO	Viviparity	<5	30-100	>1
	Mammalia	*Otocyon megalotis*	ENDO	NO	Viviparity	<5	30-100	>5
	Mammalia	*Panthera leo*	ENDO	NO	Viviparity	<5	>100	>5
	Mammalia	*Petromus typicus*	ENDO	NO	Viviparity	<5	30-100	>0.25
	Mammalia	*Procavia capensis*	ENDO	NO	Viviparity	<5	30-100	>10
	Mammalia	*Proteles cristata*	ENDO	NO	Viviparity	<5	30-100	>5
	Mammalia	*Suricata suricatta*	ENDO	NO	Viviparity	<5	30-100	>1
	Mammalia	*Vulpes chama*	ENDO	NO	Viviparity	<5	30-100	>1
	Mammalia	*Xerus inauris*	ENDO	NO	Viviparity	<5	30-100	>1
	Mammalia	*Steatomys pratensis*	ENDO	NO	Viviparity	<5	<30	>2.5
	Mammalia	*Thallomys nigricauda*	ENDO	NO	Viviparity	<5	<30	>1

TABLE B.7 - ***Continued.***

S Europe								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Endo_SmBS	Mammalia	*Galemys pyrenaicus*	ENDO	NO	Viviparity	<5	<30	>0.1
	Mammalia	*Micromys minutus*	ENDO	NO	Viviparity	<15	<30	>25
	Mammalia	*Microtus agrestis*	ENDO	NO	Viviparity	<15	<30	>10
	Mammalia	*Microtus duodecimcostatus*	ENDO	NO	Viviparity	<5	<30	>0.5
	Mammalia	*Microtus gerbei*	ENDO	NO	Viviparity	<5	<30	>0.25
	Mammalia	*Microtus lusitanicus*	ENDO	NO	Viviparity	<5	<30	>0.25
	Mammalia	*Microtus subterraneus*	ENDO	NO	Viviparity	<5	<30	>5
	Mammalia	*Mus musculus*	ENDO	NO	Viviparity	<15	<30	>75
	Mammalia	*Mustela nivalis*	ENDO	NO	Viviparity	<15	<30	>75
	Mammalia	*Rattus rattus*	ENDO	NO	Viviparity	<15	<30	>25
	Mammalia	*Suncus etruscus*	ENDO	NO	Viviparity	<5	<30	>2.5
Endo_LgEOO	Mammalia	*Crocidura suaveolens*	ENDO	NO	Viviparity	<10	<30	>10
	Mammalia	*Microtus arvalis*	ENDO	NO	Viviparity	<10	<30	>10
	Mammalia	*Myodes glareolus*	ENDO	NO	Viviparity	<10	<30	>10
	Mammalia	*Neomys fodiens*	ENDO	NO	Viviparity	<10	<30	>10
	Mammalia	*Sorex araneus*	ENDO	NO	Viviparity	<10	<30	>10
	Mammalia	*Talpa europaea*	ENDO	NO	Viviparity	<10	<30	>10
Endo_LgBS	Mammalia	*Canis lupus*	ENDO	NO	Viviparity	<15	>100	>75
	Mammalia	*Capra ibex*	ENDO	NO	Viviparity	<5	>100	<0.1
	Mammalia	*Capra pyrenaica*	ENDO	NO	Viviparity	<5	>100	<0.1
	Mammalia	*Capreolus capreolus*	ENDO	NO	Viviparity	<5	>100	>10

TABLE B.7 - *Continued.*

S Europe								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Endo_LgBS	Mammalia	*Castor fiber*	ENDO	NO	Viviparity	<5	>100	>5
	Mammalia	*Cervus elaphus*	ENDO	NO	Viviparity	<5	>100	>10
	Mammalia	*Lynx pardinus*	ENDO	NO	Viviparity	<5	>100	<0.1
	Mammalia	*Ovis aries*	ENDO	NO	Viviparity	<5	>100	>75
	Mammalia	*Rupicapra pyrenaica*	ENDO	NO	Viviparity	1	>100	<0.1
	Mammalia	*Rupicapra rupicapra*	ENDO	NO	Viviparity	<5	>100	>0.25
	Mammalia	*Sus scrofa*	ENDO	NO	Viviparity	<10	>100	>25
Water_MeFEC	Amphibia	*Bombina variegata*	ECTO	YES	Oviparity	<100	<30	>1
	Amphibia	*Calotriton asper*	ECTO	YES	Oviparity	<50	<30	<0.1
	Amphibia	*Chioglossa lusitanica*	ECTO	YES	Oviparity	<20	<30	<0.1
	Amphibia	*Salamandra salamandra*	ECTO	YES	Ovoviviparity	<50	<30	>2.5
Water_HiFEC	Amphibia	*Alytes obstetricans*	ECTO	YES	Oviparity	>100	<30	>1
	Amphibia	*Discoglossus galganoi*	ECTO	YES	Oviparity	>100	<30	>0.25
	Amphibia	*Discoglossus jeanneae*	ECTO	YES	Oviparity	>100	<30	>0.1
	Amphibia	*Discoglossus pictus*	ECTO	YES	Oviparity	>100	<30	>0.25
	Amphibia	*Discoglossus sardus*	ECTO	YES	Oviparity	>100	<30	<0.1
	Amphibia	*Epidalea calamita*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Hyla arborea*	ECTO	YES	Oviparity	>100	<30	>5
	Amphibia	*Hyla meridionalis*	ECTO	YES	Oviparity	>100	<30	>0.75
	Amphibia	*Lissotriton boscai*	ECTO	YES	Oviparity	>100	<30	>0.25
	Amphibia	*Lissotriton helveticus*	ECTO	YES	Oviparity	>100	<30	>1

TABLE B.7 - *Continued.*

S Europe								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Water_HiFEC	Amphibia	*Mesotriton alpestris*	ECTO	YES	Oviparity	>100	<30	>1
	Amphibia	*Pelobates cultripes*	ECTO	YES	Oviparity	>100	<30	>0.5
	Amphibia	*Pelodytes ibericus*	ECTO	YES	Oviparity	>100	<30	>0.1
	Amphibia	*Pelodytes punctatus*	ECTO	YES	Oviparity	>100	<30	>1
	Amphibia	*Pelophylax perezi*	ECTO	YES	Oviparity	>100	<30	>0.75
	Amphibia	*Pleurodeles waltl*	ECTO	YES	Oviparity	>100	<30	>0.25
	Amphibia	*Pseudepidalea viridis*	ECTO	YES	Oviparity	>100	<30	>5
	Amphibia	*Rana dalmatina*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Rana iberica*	ECTO	YES	Oviparity	>100	<30	>0.1
	Amphibia	*Triturus marmoratus*	ECTO	YES	Oviparity	>100	<30	>0.5
	Amphibia	*Triturus pygmaeus*	ECTO	YES	Oviparity	>100	<30	>0.1
MeBS	Mammalia	*Lepus europaeus*	ENDO	NO	Viviparity	<10	30-100	>10
	Mammalia	*Lepus granatensis*	ENDO	NO	Viviparity	<5	30-100	>0.5
	Mammalia	*Lepus timidus*	ENDO	NO	Viviparity	<5	30-100	>25
	Mammalia	*Lutra lutra*	ENDO	NO	Viviparity	<5	30-100	>25
	Mammalia	*Marmota marmota*	ENDO	NO	Viviparity	<10	30-100	>0.25
	Mammalia	*Martes foina*	ENDO	NO	Viviparity	<5	30-100	>10
	Mammalia	*Martes martes*	ENDO	NO	Viviparity	<5	30-100	>10
	Mammalia	*Meles meles*	ENDO	NO	Viviparity	<5	30-100	>10
	Mammalia	*Mustela erminea*	ENDO	NO	Viviparity	<20	30-100	>75
	Mammalia	*Mustela lutreola*	ENDO	NO	Viviparity	<10	30-100	>2.5

TABLE B.7 - *Continued.*

S Europe								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
	Mammalia	*Mustela putorius*	ENDO	NO	Viviparity	<10	30-100	>7.5
	Mammalia	*Oryctolagus cuniculus*	ENDO	NO	Viviparity	<15	30-100	>10
	Mammalia	*Vulpes vulpes*	ENDO	NO	Viviparity	<10	30-100	>75
	Reptilia	*Vipera ursinii*	ECTO	NO	Ovoviviparity	<5	30-100	<0.1
Ecto_SmBS	Reptilia	*Acanthodactylus erythrurus*	ECTO	NO	Oviparity	<10	<30	>0.75
	Reptilia	*Algyroides marchi*	ECTO	NO	Oviparity	<5	<30	<0.1
	Reptilia	*Blanus cinereus*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Chalcides bedriagai*	ECTO	NO	Ovoviviparity	<5	<30	>0.25
	Reptilia	*Chalcides striatus*	ECTO	NO	Ovoviviparity	<15	<30	>0.5
	Reptilia	*Hemidactylus turcicus*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Iberolacerta cyreni*	ECTO	NO	Oviparity	<10	<30	<0.1
	Reptilia	*Lacerta agilis*	ECTO	NO	Oviparity	<15	<30	>10
	Reptilia	*Lacerta schreiberi*	ECTO	NO	Oviparity	<20	<30	>0.1
	Reptilia	*Mauremys leprosa*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Podarcis bocagei*	ECTO	NO	Oviparity	<10	<30	<0.1
	Reptilia	*Podarcis carbonelli*	ECTO	NO	Oviparity	<5	<30	<0.1
	Reptilia	*Podarcis hispanicus*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Podarcis tiliguerta*	ECTO	NO	Oviparity	<10	<30	<0.1
	Reptilia	*Psammodromus hispanicus*	ECTO	NO	Oviparity	<5	<30	>0.5
	Reptilia	*Tarentola mauritanica*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Testudo graeca*	ECTO	NO	Oviparity	<15	<30	>5

TABLE B.7 - *Continued.*

S Europe								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
	Reptilia	*Testudo hermanni*	ECTO	NO	Oviparity	<10	<30	>0.5
	Reptilia	*Zootoca vivipara*	ECTO	NO	Ovoviviparity	<10	<30	>10
Endo_MeFEC	Mammalia	*Apodemus flavicollis*	ENDO	NO	Viviparity	<10	<30	>7.5
	Mammalia	*Apodemus sylvaticus*	ENDO	NO	Viviparity	<10	<30	>7.5
	Mammalia	*Arvicola amphibius*	ENDO	NO	Viviparity	<10	<30	>25
	Mammalia	*Arvicola sapidus*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Atelerix algirus*	ENDO	NO	Viviparity	<10	<30	>0.75
	Mammalia	*Chionomys nivalis*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Crocidura leucodon*	ENDO	NO	Viviparity	<10	<30	>5
	Mammalia	*Crocidura russula*	ENDO	NO	Viviparity	<10	<30	>2.5
	Mammalia	*Eliomys quercinus*	ENDO	NO	Viviparity	<10	<30	>2.5
	Mammalia	*Erinaceus europaeus*	ENDO	NO	Viviparity	<10	<30	>5
	Mammalia	*Felis silvestris*	ENDO	NO	Viviparity	<10	<30	>25
	Mammalia	*Glis glis*	ENDO	NO	Viviparity	<10	<30	>5
	Mammalia	*Microtus cabrerae*	ENDO	NO	Viviparity	<10	<30	>0.1
	Mammalia	*Mus spretus*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Muscardinus avellanarius*	ENDO	NO	Viviparity	<10	<30	>5
	Mammalia	*Neomys anomalus*	ENDO	NO	Viviparity	<10	<30	>5
	Mammalia	*Sciurus vulgaris*	ENDO	NO	Viviparity	<10	<30	>25
	Mammalia	*Sorex coronatus*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Sorex granarius*	ENDO	NO	Viviparity	<10	<30	<0.1

TABLE B.7 - *Continued.*

S Europe								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Endo_MeFEC	Mammalia	*Sorex minutus*	ENDO	NO	Viviparity	<10	<30	>25
	Mammalia	*Talpa occidentalis*	ENDO	NO	Viviparity	<10	<30	>0.5
Ecto_MeFEC	Reptilia	*Coronella girondica*	ECTO	NO	Oviparity	<10	30-100	>1
	Reptilia	*Emys orbicularis*	ECTO	NO	Oviparity	<20	30-100	>7.5
	Reptilia	*Hemorrhois hippocrepis*	ECTO	NO	Oviparity	<10	>100	>0.75
	Reptilia	*Hierophis viridiflavus*	ECTO	NO	Oviparity	<15	>100	>0.75
	Reptilia	*Lacerta bilineata*	ECTO	NO	Oviparity	<20	<30	>1
	Reptilia	*Lacerta viridis*	ECTO	NO	Oviparity	<20	<30	>1
	Reptilia	*Macroprotodon brevis*	ECTO	NO	Oviparity	<10	30-100	>0.5
	Reptilia	*Malpolon monspessulanus*	ECTO	NO	Oviparity	<20	>100	>1
	Reptilia	*Natrix maura*	ECTO	NO	Oviparity	<20	30-100	>1
	Reptilia	*Rhinechis scalaris*	ECTO	NO	Oviparity	<20	>100	>0.5
	Reptilia	*Timon lepidus*	ECTO	NO	Oviparity	<20	30-100	>0.75
	Reptilia	*Vipera aspis*	ECTO	NO	Oviparity	<15	30-100	>1
	Reptilia	*Vipera latastei*	ECTO	NO	Oviparity	<15	30-100	>0.75
	Reptilia	*Zamenis longissimus*	ECTO	NO	Oviparity	<10	>100	>1
	Mammalia	*Sorex minutus*	ENDO	NO	Viviparity	<10	<30	>25
	Mammalia	*Talpa occidentalis*	ENDO	NO	Viviparity	<10	<30	>0.5

TABLE B.7 - *Continued.*

W.S. Savanna								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Endo_SmBS	Mammalia	*Arvicanthis niloticus*	ENDO	NO	Viviparity	<15	<30	>5
	Mammalia	*Atelerix albiventris*	ENDO	NO	Viviparity	<10	<30	>5
	Mammalia	*Crocidura poensis*	ENDO	NO	Viviparity	<10	<30	>1
	Mammalia	*Dasymys rufulus*	ENDO	NO	Viviparity	<15	<30	>1
	Mammalia	*Funisciurus pyrropus*	ENDO	NO	Viviparity	<5	<30	>1
	Mammalia	*Gerbilliscus guineae*	ENDO	NO	Viviparity	<15	<30	>0.75
	Mammalia	*Gerbillus sp.*	ENDO	NO	Viviparity	<10	<30	>2.5
	Mammalia	*Graphiurus kelleni*	ENDO	NO	Viviparity	<5	<30	>2.5
	Mammalia	*Graphiurus lorraineus*	ENDO	NO	Viviparity	<5	<30	>2.5
	Mammalia	*Graphiurus nagtglasii*	ENDO	NO	Viviparity	<5	<30	>0.75
	Mammalia	*Heliosciurus rufobrachium*	ENDO	NO	Viviparity	<5	<30	>2.5
	Mammalia	*Lemniscomys bellieri*	ENDO	NO	Viviparity	<15	<30	>0.1
	Mammalia	*Mastomys erythroleucus*	ENDO	NO	Viviparity	<10	<30	>5
	Mammalia	*Mus setulosus*	ENDO	NO	Viviparity	<15	<30	>1
	Mammalia	*Praomys derooi*	ENDO	NO	Viviparity	<15	<30	>0.25
	Mammalia	*Praomys tullbergi*	ENDO	NO	Viviparity	<15	<30	>0.75
	Mammalia	*Steatomys caurinus*	ENDO	NO	Viviparity	<5	<30	>1
	Mammalia	*Taterillus gracilis*	ENDO	NO	Viviparity	<5	<30	>1
Water	Amphibia	*Afrixalus dorsalis*	ECTO	YES	Oviparity	>100	<30	>0.5
	Amphibia	*Amietophrynus maculatus*	ECTO	YES	Oviparity	>100	<30	>7.5
	Amphibia	*Bufo xeros*	ECTO	YES	Oviparity	>100	<30	>5

TABLE B.7 - *Continued.*

W.S. Savanna								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Water	Amphibia	*Hemisus marmoratus*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Hildebrandtia ornata*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Hoplobatrachus occipitalis*	ECTO	YES	Oviparity	>100	<30	>5
	Amphibia	*Hylarana galamensis*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Hyperolius concolor*	ECTO	YES	Oviparity	>100	<30	>0.75
	Amphibia	*Kassina senegalensis*	ECTO	YES	Oviparity	>100	<30	>2.5
	Amphibia	*Leptopelis viridis*	ECTO	YES	Oviparity	>100	<30	>1
	Amphibia	*Phrynobatrachus latifrons*	ECTO	YES	Oviparity	>100	<30	>1
	Amphibia	*Phrynobatrachus natalensis*	ECTO	YES	Oviparity	>100	<30	>2.5
Endo_MeBS	Mammalia	*Canis aureus*	ENDO	NO	Viviparity	<10	30-100	>10
	Mammalia	*Crossarchus obscurus*	ENDO	NO	Viviparity	<5	30-100	>0.25
	Mammalia	*Genetta thierryi*	ENDO	NO	Viviparity	<5	30-100	>2.5
	Mammalia	*Herpestes ichneumon*	ENDO	NO	Viviparity	<5	30-100	>10
	Mammalia	*Ictonyx striatus*	ENDO	NO	Viviparity	<5	30-100	>10
	Mammalia	*Nandinia binotata*	ENDO	NO	Viviparity	<5	30-100	>5
	Mammalia	*Procavia capensis*	ENDO	NO	Viviparity	<5	30-100	>10
	Mammalia	*Thryonomys swinderianus*	ENDO	NO	Viviparity	<5	30-100	>7.5
	Mammalia	*Vulpes pallida*	ENDO	NO	Viviparity	<5	30-100	>2.5
	Mammalia	*Xerus erythropus*	ENDO	NO	Viviparity	<5	30-100	>7.5
Ecto_LgBS	Reptilia	*Bitis arietans*	ECTO	NO	Oviparity	<100	>100	>1
	Reptilia	*Causus rhombeatus*	ECTO	NO	Oviparity	<50	30-100	>5

TABLE B.7 - *Continued.*

W.S. Savanna

Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Ecto_LgBS	Reptilia	*Chamaeleo gracilis*	ECTO	NO	Oviparity	<50	30-100	>5
	Reptilia	*Crocodylus sp.*	ECTO	NO	Oviparity	<100	>100	>5
	Reptilia	*Dispholidus typus*	ECTO	NO	Oviparity	<50	>100	>5
	Reptilia	*Grayia smythii*	ECTO	NO	Oviparity	<15	>100	>2.5
	Reptilia	*Naja melanoleuca*	ECTO	NO	Oviparity	<50	>100	>5
	Reptilia	*Psammophis phillipsi*	ECTO	NO	Oviparity	<10	>100	>0.5
	Reptilia	*Rhamphiophis oxyrhynchus*	ECTO	NO	Oviparity	<20	>100	>5
	Reptilia	*Scaphiophis albopunctatus*	ECTO	NO	Oviparity	<20	>100	>2.5
	Reptilia	*Toxicodryas blandingii*	ECTO	NO	Oviparity	<20	>100	>2.5
	Reptilia	*Varanus niloticus*	ECTO	NO	Oviparity	<50	>100	>1
Endo_LoFEC	Mammalia	*Anomalurus beecrofti*	ENDO	NO	Viviparity	1	30-100	>2.5
	Mammalia	*Cephalophus niger*	ENDO	NO	Viviparity	1	30-100	>0.75
	Mammalia	*Erythrocebus patas*	ENDO	NO	Viviparity	1	30-100	>5
	Mammalia	*Felovia vae*	ENDO	NO	Viviparity	1	<30	>0.1
	Mammalia	*Galagoides demidoff*	ENDO	NO	Viviparity	1	<30	>5
	Mammalia	*Giraffa camelopardalis*	ENDO	NO	Viviparity	1	>100	>1
	Mammalia	*Panthera leo*	ENDO	NO	Viviparity	<10	>100	>5
	Mammalia	*Papio anubis*	ENDO	NO	Viviparity	1	30-100	>7.5
	Mammalia	*Papio papio*	ENDO	NO	Viviparity	1	>100	>0.25
	Mammalia	*Phataginus tricuspis*	ENDO	NO	Viviparity	1	30-100	>5
	Mammalia	*Redunca redunca*	ENDO	NO	Viviparity	1	>100	>5

TABLE B.7 - *Continued.*

W.S. Savanna								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Endo_LoFEC	Mammalia	*Sylvicapra grimmia*	ENDO	NO	Viviparity	1	>100	>10
	Mammalia	*Tragelaphus scriptus*	ENDO	NO	Viviparity	1	>100	>10
Ecto_SmBS	Reptilia	*Agama agama*	ECTO	NO	Oviparity	<10	<30	>2.5
	Reptilia	*Agama boueti*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Agama boulengeri*	ECTO	NO	Oviparity	<10	<30	>0.1
	Reptilia	*Chamaeleo africanus*	ECTO	NO	Oviparity	<20	<30	>2.5
	Reptilia	*Hemidactylus angulatus*	ECTO	NO	Oviparity	<5	<30	>2.5
	Reptilia	*Hemidactylus brookii*	ECTO	NO	Oviparity	<5	<30	>2.5
	Reptilia	*Hemidactylus fasciatus*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Hemidactylus mabouia*	ECTO	NO	Oviparity	<5	<30	>2.5
	Reptilia	*Hemidactylus muriceus*	ECTO	NO	Oviparity	<5	<30	>0.75
	Reptilia	*Kinixys belliana*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Lygodactylus gutturalis*	ECTO	NO	Oviparity	<5	<30	>1
	Reptilia	*Ptyodactylus ragazzi*	ECTO	NO	Oviparity	<5	<30	>2.5
	Reptilia	*Tarentola annularis*	ECTO	NO	Oviparity	<5	<30	>5
	Reptilia	*Tarentola ephippiata*	ECTO	NO	Oviparity	<5	<30	>2.5
	Reptilia	*Tarentola parvicarinata*	ECTO	NO	Oviparity	<5	<30	>0.25
	Reptilia	*Trachylepis affinis*	ECTO	NO	Oviparity	<10	<30	>1
	Reptilia	*Trachylepis quinquetaeniata*	ECTO	NO	Oviparity	<10	<30	>2.5
	Reptilia	*Tropiocolotes tripolitanus*	ECTO	NO	Oviparity	<5	<30	>2.5
Endo_MeFEC	Mammalia	*Gerbilliscus kempi*	ENDO	NO	Viviparity	<15	<30	>2.5

TABLE B.7 - *Continued.*

W.S. Savanna								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Endo_MeFEC	Mammalia	*Lemniscomys striatus*	ENDO	NO	Viviparity	<15	<30	>2.5
	Mammalia	*Lemniscomys zebra*	ENDO	NO	Viviparity	<15	<30	>2.5
	Mammalia	*Mus haussa*	ENDO	NO	Viviparity	<15	<30	>2.5
	Mammalia	*Praomys daltoni*	ENDO	NO	Viviparity	<15	<30	>2.5
	Mammalia	*Uranomys ruddi*	ENDO	NO	Viviparity	<15	<30	>2.5
Ecto_MeBS	Reptilia	*Afronatrix anoscopus*	ECTO	NO	Oviparity	<15	30-100	>1
	Reptilia	*Afrotyphlops punctatus*	ECTO	NO	Oviparity	<15	30-100	>2.5
	Reptilia	*Boaedon fuliginosus*	ECTO	NO	Oviparity	<15	30-100	>5
	Reptilia	*Boaedon lineatus*	ECTO	NO	Oviparity	<15	30-100	>2.5
	Reptilia	*Causus maculatus*	ECTO	NO	Oviparity	<20	30-100	>5
	Reptilia	*Chamaeleo senegalensis*	ECTO	NO	Oviparity	<100	30-100	>2.5
	Reptilia	*Crotaphopeltis hotamboeia*	ECTO	NO	Oviparity	<20	30-100	>1
	Reptilia	*Dasypeltis fasciata*	ECTO	NO	Oviparity	<15	30-100	>2.5
	Reptilia	*Echis leucogaster*	ECTO	NO	Oviparity	<20	30-100	>1
	Reptilia	*Echis ocellatus*	ECTO	NO	Oviparity	<20	30-100	>1
	Reptilia	*Gerrhosaurus major*	ECTO	NO	Oviparity	<10	30-100	>2.5
	Reptilia	*Meizodon coronatus*	ECTO	NO	Viviparity	<10	30-100	>2.5
	Reptilia	*Philothamnus irregularis*	ECTO	NO	Oviparity	<20	30-100	>2.5
	Reptilia	*Philothamnus semivariegatus*	ECTO	NO	Oviparity	<20	30-100	>2.5
	Reptilia	*Psammophis elegans*	ECTO	NO	Oviparity	<10	30-100	>0.5
	Reptilia	*Psammophis lineatus*	ECTO	NO	Oviparity	<10	30-100	>1

TABLE B.7 - ***Continued.***

W.S. Savanna								
Group	Class	Taxa	Thermoregulation	Water	Reproduction	Fecundity (number of eggs)	Body Size (cm)	EOO (millions of km^2)
Ecto_MeBS	Reptilia	*Trachylepis albilabris*	ECTO	NO	Oviparity	<10	30-100	>0.75
	Reptilia	*Uromastyx dispar*	ECTO	NO	Oviparity	<20	30-100	>1

TABLE B.8 - ***Number of observations (N) for each taxa and each dryland used to developed ecological niche-based models, and true-skill statistics of models. Four model algorithms were used, namely: generalized linear models (GLM); generalized boosted models (GBM); artificial neural networks (ANN); and maximum entropy (MaxEnt). PA1 and PA2 refer to two pseudo-absence datasets used for training the models. Models used for species richness predictions are highlighted in bold (TSS >0.7, except for Caatinga TSS >0.5).***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
AMPHIBIA									
Crinia deserticola	90	0.380	0.269	0.587	0.656	0.556	0.579	0.588	0.499
Crinia riparia	58	**0.815**	**0.876**	**0.872**	**0.820**	**0.909**	**0.811**	**0.947**	**0.956**
Limnodynastes peronii	958	**0.878**	**0.884**	**0.884**	**0.894**	**0.886**	**0.872**	**0.878**	**0.885**
Limnodynastes tasmaniensis	2361	**0.709**	**0.722**	**0.730**	**0.746**	**0.714**	**0.751**	**0.722**	**0.744**
Litoria adelaidensis	124	**0.840**	**0.932**	**0.838**	**0.857**	**0.841**	**0.923**	**0.840**	**0.919**
Litoria australis	221	**0.806**	**0.787**	**0.797**	**0.822**	**0.821**	**0.773**	**0.814**	**0.799**
Litoria caerulea	1257	0.630	0.659	0.655	0.665	0.632	0.670	0.666	0.648
Litoria gilleni	39	**0.835**	**0.952**	**0.705**	**0.831**	**0.736**	**0.859**	**0.935**	**0.954**
Litoria maini	207	**0.735**	0.695	**0.715**	0.619	0.683	**0.711**	**0.702**	0.636
Litoria platycephala	258	0.509	0.554	0.598	0.623	0.519	0.665	0.568	0.575
Litoria rubella	1243	0.481	0.421	0.491	0.451	0.513	0.481	0.500	0.455
Neobatrachus centralis	214	0.651	**0.727**	0.652	**0.723**	0.662	0.663	0.640	**0.735**
Neobatrachus kunapalari	179	**0.809**	**0.850**	**0.812**	**0.833**	0.694	**0.812**	**0.830**	**0.819**
Neobatrachus pictus	359	**0.885**	**0.828**	**0.896**	**0.860**	**0.922**	**0.869**	**0.900**	**0.834**
Notaden nichollsi	163	0.669	0.607	0.690	0.642	0.696	0.609	0.650	0.648
Platyplectrum ornatum	794	**0.765**	**0.719**	**0.792**	**0.748**	**0.761**	**0.727**	**0.792**	**0.734**
Platyplectrum spenceri	98	**0.960**	0.666	**0.940**	**0.862**	**0.897**	**0.904**	**0.960**	**0.901**

TABLE B.8 - ***Continued.***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
MAMMALIA									
Antechinomys laniger	229	0.542	0.509	0.567	0.547	0.656	0.580	0.627	0.554
Canis lupus dingo	1146	0.623	0.616	0.688	0.674	0.692	**0.702**	**0.706**	**0.704**
Chaeropus ecaudatus	23	0.577	**0.753**	0.481	**0.953**	0.545	**0.880**	0.533	**0.822**
Dasycercus blythi	153	**0.755**	**0.866**	**0.788**	**0.794**	**0.796**	**0.846**	**0.807**	**0.805**
Lasiorhinus latifrons	344	**0.822**	**0.846**	**0.843**	**0.887**	**0.908**	**0.937**	**0.875**	**0.888**
Leggadina forresti	356	0.429	0.682	0.663	0.693	**0.718**	**0.734**	0.638	**0.742**
Leporillus apicalis	65	0.520	0.695	0.633	**0.821**	0.333	0.668	0.575	**0.758**
Macropus fuliginosus	2232	**0.749**	**0.748**	**0.775**	**0.751**	**0.814**	**0.817**	**0.768**	**0.754**
Macropus giganteus	2184	**0.797**	**0.801**	**0.808**	**0.823**	**0.831**	0.000	**0.815**	**0.834**
Macropus robustus	19	**0.730**	**0.958**	**0.973**	**0.981**	**0.983**	**0.996**	**0.953**	**0.953**
Macropus rufus	4166	0.518	0.515	0.561	0.546	0.612	0.649	0.627	0.605
Macrotis lagotis	381	0.697	0.681	**0.753**	**0.737**	0.657	0.674	**0.773**	**0.731**
Ningaui ridei	210	**0.784**	**0.777**	**0.783**	**0.809**	**0.748**	**0.818**	**0.798**	**0.823**
Notomys alexis	646	**0.714**	**0.710**	**0.746**	**0.720**	**0.742**	**0.712**	**0.776**	**0.752**
Notomys amplus	18	**0.937**	0.518	**0.746**	0.506	**0.901**	0.450	**0.847**	0.680
Notomys fuscus	175	**0.800**	**0.768**	**0.853**	**0.847**	**0.825**	**0.848**	**0.834**	**0.821**
Notomys longicaudatus	41	0.687	**0.747**	0.635	**0.733**	**0.720**	0.000	**0.792**	**0.773**
Notoryctes typhlops	73	**0.733**	**0.752**	**0.730**	0.659	0.596	0.584	**0.707**	0.615
Petrogale lateralis	188	**0.854**	**0.874**	**0.900**	**0.863**	**0.877**	**0.889**	**0.909**	**0.888**
Petrogale xanthopus	116	**0.903**	**0.961**	**0.862**	**0.961**	**0.866**	**0.947**	**0.870**	**0.961**
Planigale gilesi	181	0.639	**0.800**	0.679	**0.809**	0.695	**0.776**	**0.770**	**0.750**

TABLE B.8 - ***Continued.***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Planigale ingrami	158	0.672	**0.713**	0.615	0.658	0.669	**0.735**	0.609	**0.766**
Planigale tenuirostris	173	0.626	**0.720**	0.612	**0.704**	0.692	0.559	0.597	**0.752**
Pseudantechinus macdonnellensis	168	**0.801**	**0.733**	**0.874**	**0.833**	**0.803**	**0.784**	**0.845**	**0.800**
Pseudomys australis	118	**0.759**	**0.755**	**0.752**	0.631	**0.779**	**0.723**	**0.762**	0.611
Pseudomys bolami	166	0.631	**0.838**	**0.864**	**0.844**	**0.811**	**0.821**	**0.867**	**0.872**
Pseudomys desertor	367	0.613	0.667	0.645	**0.764**	0.676	0.000	0.698	**0.792**
Pseudomys gouldii	44	0.619	0.578	0.678	**0.732**	**0.732**	**0.809**	**0.747**	**0.740**
Pseudomys hermannsburgensis	1080	0.623	0.634	0.679	0.682	**0.722**	0.678	0.691	**0.710**
Rattus villosissimus	329	0.566	0.556	0.597	0.588	0.614	0.536	0.650	0.637
Sminthopsis crassicaudata	1050	0.595	0.620	0.599	0.590	0.673	0.634	0.609	0.607
Sminthopsis dolichura	111	**0.816**	**0.903**	**0.906**	**0.930**	**0.933**	**0.909**	**0.938**	**0.927**
Sminthopsis hirtipes	45	**0.954**	0.581	**0.884**	0.619	**0.852**	0.619	**0.954**	0.620
Sminthopsis macroura	848	0.490	0.482	0.527	0.603	0.619	0.640	0.580	0.641
Sminthopsis murina	619	**0.787**	**0.800**	**0.803**	**0.826**	**0.825**	**0.811**	**0.813**	**0.824**
Sminthopsis ooldea	220	**0.825**	**0.796**	**0.823**	**0.774**	**0.835**	**0.719**	**0.843**	**0.790**
Sminthopsis psammophila	31	**0.869**	**0.953**	0.598	**0.786**	**0.954**	**0.981**	**0.785**	**0.953**
Sminthopsis youngsoni	186	**0.811**	**0.744**	**0.839**	**0.783**	**0.794**	**0.729**	**0.848**	**0.803**
Tachyglossus aculeatus	4317	0.628	0.600	0.686	0.674	0.691	0.659	0.665	0.653
Trichosurus vulpecula	2579	**0.734**	**0.714**	**0.764**	**0.776**	0.000	**0.771**	**0.758**	**0.771**
Zyzomys pedunculatus	20	0.459	**0.937**	**0.703**	**0.979**	0.580	**0.709**	**0.928**	**0.952**
REPTILIA									
Acanthophis antarcticus	207	**0.742**	**0.705**	**0.765**	**0.705**	0.695	0.695	**0.764**	**0.734**

TABLE B.8 - ***Continued.***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Acanthophis pyrrhus	69	0.647	**0.778**	0.644	0.620	**0.786**	0.000	**0.804**	**0.733**
Amalosia rhombifer	343	0.647	**0.778**	0.644	0.620	**0.786**	0.000	**0.804**	**0.733**
Antaresia stimsoni	278	0.462	0.463	0.376	0.531	0.366	0.367	0.475	0.525
Aprasia inaurita	128	**0.811**	**0.889**	**0.926**	**0.898**	**0.925**	**0.875**	**0.941**	**0.898**
Aprasia pseudopulchella	29	0.470	**0.791**	**0.787**	**0.953**	0.473	**0.787**	**0.930**	**0.953**
Aspidites ramsayi	164	0.476	0.461	0.557	0.493	0.468	0.493	0.492	0.467
Austrotyphlops bituberculatus	509	0.622	0.619	0.667	0.640	0.626	0.648	0.643	0.657
Austrotyphlops centralis	23	**0.966**	**0.954**	**0.983**	**0.959**	0.582	**0.982**	**0.953**	**0.953**
Austrotyphlops diversus	105	**0.806**	**0.721**	**0.710**	**0.712**	**0.813**	0.651	**0.771**	**0.794**
Austrotyphlops endoterus	221	0.397	0.593	0.649	0.594	0.654	0.572	0.623	0.651
Austrotyphlops grypus	173	0.679	**0.704**	**0.761**	**0.720**	**0.726**	0.620	0.675	0.692
Austrotyphlops proximus	133	**0.840**	**0.812**	**0.883**	**0.840**	**0.833**	**0.775**	**0.872**	**0.777**
Brachyurophis australis	170	**0.754**	**0.776**	**0.764**	**0.813**	**0.772**	**0.776**	**0.748**	**0.881**
Brachyurophis fasciolatus	63	0.310	0.482	0.487	0.454	0.484	0.353	0.511	0.512
Brachyurophis incinctus	52	**0.910**	0.572	**0.754**	**0.730**	0.574	0.580	**0.885**	0.692
Brachyurophis semifasciatus	238	0.685	0.634	0.631	0.624	0.580	0.626	0.684	0.664
Carlia munda	678	**0.717**	**0.759**	**0.747**	**0.782**	**0.767**	**0.784**	**0.745**	**0.785**
Carlia triacantha	295	0.685	0.685	**0.773**	**0.724**	**0.737**	**0.768**	**0.759**	**0.769**
Christinus marmoratus	818	**0.823**	**0.838**	**0.833**	**0.819**	**0.836**	**0.819**	**0.836**	**0.842**
Crenadactylus ocellatus	332	**0.734**	**0.719**	**0.735**	**0.745**	**0.762**	**0.740**	**0.750**	**0.789**
Cryptoblepharus boutonii	19	0.694	0.603	**0.740**	**0.702**	0.367	**0.728**	0.692	0.484
Cryptoblepharus pannosus	361	0.500	0.542	0.490	0.542	0.495	0.565	0.493	0.602

TABLE B.8 - ***Continued.***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Ctenophorus caudicinctus	579	**0.720**	0.676	**0.710**	0.657	0.682	**0.711**	**0.723**	**0.726**
Ctenophorus clayi	96	**0.798**	**0.781**	**0.807**	**0.761**	**0.712**	0.553	**0.819**	0.673
Ctenophorus cristatus	452	**0.834**	**0.832**	**0.797**	**0.839**	**0.768**	**0.866**	**0.861**	**0.868**
Ctenophorus decresii	148	**0.930**	**0.880**	**0.912**	**0.890**	**0.862**	**0.797**	**0.920**	**0.893**
Ctenophorus fionni	136	**0.938**	**0.880**	**0.917**	**0.876**	**0.958**	**0.889**	**0.963**	**0.880**
Ctenophorus fordi	614	**0.768**	**0.757**	**0.813**	**0.789**	**0.792**	**0.793**	**0.786**	**0.789**
Ctenophorus gibba	61	**0.822**	**0.899**	**0.805**	**0.878**	**0.879**	**0.811**	**0.922**	**0.956**
Ctenophorus isolepis	1141	0.563	0.558	0.526	0.549	0.568	0.491	0.584	0.576
Ctenophorus maculosus	35	**0.823**	**0.825**	**0.956**	**0.969**	**0.983**	**0.958**	**0.954**	**0.956**
Ctenophorus nuchalis	1551	0.492	0.448	0.510	0.458	0.519	0.482	0.535	0.485
Ctenophorus pictus	932	**0.725**	0.700	**0.716**	**0.727**	**0.754**	**0.738**	**0.732**	**0.715**
Ctenophorus reticulatus	568	**0.708**	**0.705**	0.685	0.686	**0.723**	**0.706**	**0.722**	0.686
Ctenophorus rufescens	37	**0.811**	0.611	**0.810**	**0.954**	**0.914**	**0.815**	**0.811**	**0.953**
Ctenophorus tjantjalka	24	**0.953**	**0.827**	**0.953**	**0.752**	**0.953**	**0.877**	**0.952**	**0.936**
Ctenophorus vadnappa	88	**0.928**	**0.712**	**0.958**	**0.945**	**0.913**	**0.974**	**0.959**	**0.958**
Ctenotus alacer	84	**0.958**	**0.858**	**0.958**	**0.899**	**0.903**	**0.840**	**0.953**	**0.899**
Ctenotus ariadnae	66	0.660	0.661	**0.807**	**0.709**	**0.703**	**0.748**	0.684	**0.719**
Ctenotus atlas	349	**0.843**	**0.834**	**0.837**	**0.840**	**0.831**	**0.847**	**0.861**	**0.853**
Ctenotus brachyonyx	166	**0.861**	**0.878**	**0.854**	**0.876**	**0.805**	**0.884**	**0.843**	**0.903**
Ctenotus brooksi	222	0.589	0.499	0.623	0.567	0.508	0.496	0.641	0.518
Ctenotus calurus	127	**0.746**	0.652	**0.781**	**0.763**	0.000	**0.708**	**0.740**	0.693
Ctenotus dux	92	**0.809**	0.507	**0.820**	**0.737**	0.699	0.668	**0.807**	**0.778**

TABLE B.8 - ***Continued.***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Ctenotus grandis	118	0.670	**0.797**	0.643	**0.713**	0.612	**0.732**	**0.716**	**0.729**
Ctenotus greeri	64	0.673	0.683	**0.797**	**0.752**	0.690	0.699	0.564	**0.801**
Ctenotus hanloni	73	0.665	**0.763**	0.609	0.689	**0.738**	0.554	0.675	**0.812**
Ctenotus helenae	501	0.564	0.594	0.580	0.634	0.581	0.576	0.568	0.605
Ctenotus leae	150	**0.713**	0.676	**0.766**	**0.724**	0.639	0.569	**0.736**	**0.709**
Ctenotus leonhardii	733	0.524	0.550	0.584	0.645	0.575	0.561	0.569	0.639
Ctenotus nasutus	54	0.699	**0.790**	0.666	**0.782**	**0.707**	**0.746**	**0.708**	0.699
Ctenotus olympicus	253	**0.727**	**0.710**	**0.761**	**0.747**	**0.813**	**0.819**	**0.828**	**0.803**
Ctenotus pantherinus	509	0.542	0.451	0.528	0.475	0.582	0.506	0.574	0.530
Ctenotus piankai	279	0.683	0.684	**0.786**	**0.740**	**0.705**	0.672	**0.746**	**0.721**
Ctenotus quattuordecimlineatus	277	**0.740**	**0.761**	**0.782**	0.683	**0.717**	**0.715**	**0.778**	**0.726**
Ctenotus regius	878	0.698	**0.723**	**0.713**	**0.724**	**0.761**	**0.730**	**0.709**	**0.741**
Ctenotus robustus	1465	0.570	0.602	0.612	0.633	0.567	0.592	0.615	0.644
Ctenotus saxatilis	518	0.641	0.636	**0.716**	0.641	0.657	0.646	**0.710**	0.675
Ctenotus schomburgkii	1250	0.530	0.542	0.518	0.555	0.518	0.583	0.558	0.583
Ctenotus septenarius	55	0.469	0.596	**0.769**	**0.814**	0.583	**0.856**	0.650	**0.809**
Ctenotus strauchii	267	0.672	**0.708**	0.690	0.689	**0.728**	0.639	0.632	0.682
Ctenotus taeniolatus	914	**0.734**	**0.733**	**0.812**	**0.787**	**0.811**	**0.780**	**0.818**	**0.793**
Ctenotus uber	83	0.497	0.627	0.550	0.652	0.535	0.610	0.552	0.623
Cyclodomorphus branchialis	22	0.470	0.199	0.700	0.572	**0.806**	0.452	**0.701**	0.649
Cyclodomorphus melanops	339	0.683	0.641	0.615	0.644	0.629	0.646	0.662	0.637
Cyclodomorphus venustus	33	0.485	0.524	0.517	0.524	0.380	0.460	0.566	0.608

TABLE B.8 - ***Continued.***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Delma australis	456	**0.746**	**0.735**	0.698	**0.766**	0.696	**0.776**	**0.739**	**0.777**
Delma borea	264	**0.800**	**0.757**	**0.753**	**0.735**	**0.747**	**0.716**	**0.781**	**0.744**
Delma butleri	310	0.676	0.691	0.651	0.668	**0.715**	0.628	**0.702**	0.616
Delma haroldi	65	**0.743**	0.677	**0.828**	0.688	0.688	0.643	**0.795**	**0.724**
Delma molleri	76	**0.940**	**0.957**	**0.853**	**0.957**	**0.948**	**0.957**	**0.905**	**0.918**
Delma tincta	358	0.446	0.447	0.473	0.460	0.411	0.453	0.489	0.526
Demansia psammophis	693	0.567	0.646	0.579	0.654	0.614	0.632	0.593	0.650
Diplodactylus conspicillatus	710	0.456	0.501	0.475	0.546	0.480	0.468	0.510	0.588
Diplodactylus furcosus	156	**0.954**	**0.953**	**0.963**	**0.937**	**0.922**	**0.931**	**0.962**	**0.953**
Diplodactylus galeatus	59	**0.730**	**0.954**	**0.823**	**0.956**	**0.843**	**0.864**	**0.906**	**0.956**
Diplodactylus granariensis	225	**0.820**	**0.868**	**0.846**	**0.814**	**0.733**	**0.782**	**0.864**	**0.853**
Diplodactylus tessellatus	535	0.677	0.659	0.686	**0.710**	**0.723**	0.655	0.678	**0.721**
Diplodactylus vittatus	722	**0.803**	**0.738**	**0.784**	**0.754**	**0.789**	**0.764**	**0.779**	**0.757**
Diporiphora lalliae	153	**0.764**	**0.749**	**0.748**	**0.702**	**0.801**	**0.707**	**0.773**	0.676
Diporiphora nobbi	477	**0.756**	**0.767**	**0.784**	**0.800**	**0.769**	**0.798**	**0.779**	**0.796**
Diporiphora winneckei	280	0.610	0.583	0.596	0.648	0.579	0.503	0.614	0.640
Echiopsis curta	119	**0.750**	**0.906**	**0.788**	**0.874**	0.624	**0.854**	**0.818**	**0.918**
Egernia formosa	88	**0.713**	**0.818**	**0.896**	0.663	0.602	**0.762**	**0.922**	**0.795**
Egernia stokesii	193	**0.734**	0.694	**0.754**	**0.757**	**0.716**	0.699	**0.725**	**0.752**
Egernia striolata	914	**0.779**	**0.759**	**0.817**	**0.793**	**0.808**	**0.803**	**0.795**	**0.784**
Emydura macquarii	174	**0.746**	0.636	**0.793**	0.697	**0.760**	0.659	**0.742**	0.652
Eremiascincus fasciolatus	458	0.516	0.576	0.605	0.690	0.562	0.629	0.619	0.624

TABLE B.8 - ***Continued.***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Eremiascincus richardsonii	632	0.480	0.499	0.545	0.490	0.494	0.000	0.488	0.513
Eulamprus quoyii	815	**0.857**	**0.870**	**0.888**	**0.893**	**0.844**	**0.885**	**0.878**	**0.891**
Furina diadema	339	**0.756**	**0.733**	**0.788**	**0.756**	**0.797**	**0.752**	**0.766**	**0.730**
Furina ornata	341	0.593	0.654	0.585	0.649	0.511	0.618	0.599	0.669
Gehyra lazelli	116	**0.917**	**0.961**	**0.870**	**0.895**	**0.896**	**0.954**	**0.883**	**0.946**
Gehyra montium	126	**0.785**	**0.922**	**0.849**	**0.880**	0.553	**0.772**	**0.856**	**0.886**
Gehyra purpurascens	556	0.494	0.532	0.559	0.546	0.541	0.500	0.531	0.534
Gehyra variegata	3409	0.433	0.439	0.430	0.435	0.460	0.467	0.462	0.465
Hemiergis decresiensis	507	**0.887**	**0.911**	**0.897**	**0.918**	**0.875**	**0.886**	**0.887**	**0.912**
Hemiergis millewae	83	**0.897**	**0.958**	**0.856**	**0.920**	0.000	**0.914**	**0.868**	**0.906**
Hemiergis peronii	488	**0.933**	**0.914**	**0.946**	**0.920**	**0.952**	**0.873**	**0.940**	**0.919**
Heteronotia binoei	4076	0.298	0.306	0.304	0.333	0.404	0.409	0.337	0.365
Heteronotia spelea	56	0.666	**0.740**	**0.732**	**0.847**	0.640	**0.704**	**0.776**	**0.860**
Lampropholis guichenoti	1434	**0.908**	**0.899**	**0.911**	**0.895**	**0.915**	**0.897**	**0.913**	**0.915**
Lerista aericeps	51	0.612	**0.880**	**0.743**	**0.946**	**0.792**	**0.812**	**0.735**	**0.955**
Lerista bipes	470	0.646	0.628	0.641	0.639	0.636	0.641	0.671	0.638
Lerista bougainvillii	597	**0.825**	**0.843**	**0.843**	**0.856**	**0.868**	**0.862**	**0.832**	**0.859**
Lerista desertorum	329	**0.847**	**0.817**	**0.831**	**0.812**	**0.865**	0.000	**0.850**	**0.845**
Lerista dorsalis	218	**0.866**	**0.893**	**0.870**	**0.877**	**0.877**	0.000	**0.883**	**0.851**
Lerista edwardsae	154	**0.932**	**0.899**	**0.923**	**0.916**	**0.899**	**0.899**	**0.912**	**0.895**
Lerista frosti	52	**0.754**	**0.768**	**0.852**	**0.754**	**0.728**	**0.755**	**0.754**	**0.844**
Lerista labialis	632	0.648	0.664	0.667	0.693	**0.706**	**0.721**	0.655	0.674

TABLE B.8 - ***Continued.***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Lerista orientalis	96	**0.862**	**0.834**	**0.937**	**0.840**	**0.851**	**0.778**	**0.869**	**0.854**
Lerista picturata	77	**0.793**	**0.737**	**0.890**	**0.884**	**0.873**	**0.871**	**0.882**	**0.873**
Lerista punctatovittata	564	**0.794**	**0.809**	**0.801**	**0.815**	**0.827**	**0.795**	**0.794**	**0.812**
Lerista taeniata	39	0.460	0.579	0.592	0.517	0.446	0.420	0.482	0.425
Lerista terdigitata	53	**0.925**	**0.864**	**0.864**	**0.842**	**0.827**	**0.746**	**0.843**	**0.852**
Lerista xanthura	72	0.446	0.310	0.660	0.514	0.561	0.562	0.499	0.577
Lialis burtonis	1432	0.346	0.363	0.404	0.421	0.477	0.329	0.443	0.428
Liopholis inornata	618	0.569	0.591	0.616	0.634	0.655	0.653	0.632	0.637
Liopholis kintorei	56	0.629	0.684	0.617	0.602	0.666	0.589	0.673	0.652
Liopholis margaretae	35	**0.789**	**0.960**	**0.817**	**0.966**	0.531	**0.971**	**0.870**	**0.954**
Liopholis multiscutata	20	**0.817**	**0.914**	**0.890**	**0.952**	0.696	0.000	**0.783**	**0.952**
Liopholis striata	137	**0.732**	0.671	**0.766**	**0.745**	**0.738**	**0.736**	**0.738**	0.639
Liopholis whitii	655	**0.906**	**0.923**	**0.921**	**0.925**	**0.903**	**0.893**	**0.925**	**0.928**
Lophognathus gilberti	697	0.692	0.684	**0.702**	**0.732**	**0.722**	**0.707**	**0.701**	**0.716**
Lophognathus longirostris	555	0.636	0.634	0.637	0.672	0.629	0.668	0.668	0.676
Lucasium byrnei	211	**0.806**	**0.795**	**0.803**	**0.765**	**0.801**	**0.843**	**0.874**	**0.780**
Lucasium damaeum	813	0.618	**0.705**	**0.714**	0.690	**0.748**	**0.747**	**0.745**	0.699
Lucasium steindachneri	150	**0.828**	**0.728**	**0.858**	**0.758**	**0.773**	**0.702**	**0.838**	**0.734**
Lucasium stenodactylum	591	0.482	0.506	0.620	0.512	0.548	0.514	0.632	0.548
Lucasium stenodactylus	224	0.614	0.628	0.614	0.691	0.558	0.623	0.659	0.655
Menetia greyii	2703	0.367	0.385	0.414	0.408	0.421	0.390	0.436	0.438
Moloch horridus	575	0.607	0.633	0.590	0.597	0.641	0.593	0.619	0.638

TABLE B.8 - ***Continued.***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Morelia spilota	524	**0.736**	**0.742**	**0.813**	**0.774**	0.619	**0.816**	**0.811**	**0.835**
Morethia adelaidensis	482	**0.732**	0.581	**0.730**	**0.704**	**0.765**	**0.710**	**0.743**	**0.712**
Morethia lineoocellata	113	0.627	0.636	0.677	0.596	0.629	0.696	0.664	0.691
Morethia obscura	867	**0.815**	**0.849**	**0.826**	**0.840**	**0.830**	**0.865**	**0.833**	**0.873**
Morethia taeniopleura	68	**0.918**	**0.825**	**0.950**	**0.748**	**0.879**	0.658	**0.920**	**0.812**
Nephrurus amyae	61	0.653	**0.849**	**0.711**	**0.879**	**0.713**	**0.812**	**0.788**	**0.872**
Nephrurus deleani	21	**0.976**	**0.963**	**0.991**	**0.990**	**0.997**	**0.982**	**0.962**	**0.957**
Nephrurus laevissimus	236	0.689	0.682	0.699	0.699	0.650	0.680	**0.726**	**0.730**
Nephrurus levis	804	0.545	0.537	0.598	0.588	0.604	0.602	0.612	0.602
Nephrurus stellatus	103	**0.867**	0.668	**0.913**	**0.892**	**0.847**	**0.912**	**0.890**	**0.922**
Notechis scutatus	672	**0.839**	**0.819**	**0.853**	**0.846**	**0.835**	**0.827**	**0.833**	**0.835**
Notoscincus ornatus	256	0.697	0.634	0.692	0.689	**0.711**	**0.705**	0.670	0.670
Oedura marmorata	352	0.638	0.554	0.570	0.596	0.626	0.670	0.622	0.634
Ophidiocephalus taeniatus	26	**0.936**	**0.786**	**0.963**	**0.954**	**0.994**	**0.956**	**0.953**	**0.952**
Oxyuranus microlepidotus	30	0.625	**0.910**	0.619	**0.909**	0.607	**0.785**	0.618	**0.953**
Parasuta monachus	192	0.596	0.584	0.619	0.653	0.580	0.583	0.615	0.610
Parasuta nigriceps	262	**0.882**	**0.863**	**0.870**	**0.846**	0.000	**0.827**	**0.884**	**0.851**
Parasuta spectabilis	162	**0.732**	0.647	0.684	0.697	0.672	**0.777**	0.698	0.630
Pogona minor	889	0.609	0.621	0.601	0.593	0.665	0.625	0.651	0.619
Pogona mitchelli	58	0.639	**0.820**	**0.702**	**0.866**	0.576	0.676	0.660	**0.872**
Pogona vitticeps	1392	0.585	0.619	0.632	0.619	0.669	0.684	0.632	0.641
Proablepharus kinghorni	63	0.593	0.490	0.647	**0.728**	**0.796**	0.679	0.698	**0.741**

TABLE B.8 - ***Continued.***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Proablepharus reginae	84	0.617	**0.850**	**0.787**	**0.776**	**0.714**	**0.749**	**0.807**	**0.799**
Pseudechis australis	958	0.346	0.312	0.358	0.372	0.405	0.191	0.360	0.339
Pseudechis porphyriacus	1100	**0.872**	**0.855**	**0.873**	**0.877**	**0.860**	**0.856**	**0.884**	**0.877**
Pseudonaja aspidorhyncha	93	**0.722**	0.490	**0.875**	**0.888**	**0.866**	**0.714**	**0.906**	**0.886**
Pseudonaja inframacula	79	**0.970**	**0.904**	**0.958**	**0.839**	0.000	**0.917**	**0.958**	**0.894**
Pseudonaja mengdeni	45	0.582	0.421	**0.742**	0.352	0.454	0.368	**0.707**	0.355
Pseudonaja modesta	572	0.564	0.507	0.509	0.524	0.504	0.495	0.527	0.553
Pseudonaja textilis	1434	0.654	**0.721**	0.678	**0.730**	0.693	**0.733**	0.679	**0.723**
Pygopus lepidopodus	514	**0.752**	**0.787**	**0.708**	**0.792**	**0.731**	**0.772**	**0.731**	**0.798**
Pygopus nigriceps	370	0.476	0.485	0.448	0.466	0.438	0.288	0.450	0.498
Pygopus schraderi	205	0.670	0.668	**0.705**	0.693	**0.771**	0.660	**0.705**	0.699
Ramphotyphlops bicolor	200	**0.792**	0.669	**0.765**	0.637	**0.724**	0.692	**0.788**	0.645
Ramphotyphlops braminus	15	**0.942**	**0.830**	**0.935**	**0.918**	**0.952**	**0.991**	**0.952**	**0.951**
Rhynchoedura ornata	1322	0.446	0.432	0.475	0.490	0.471	0.462	0.479	0.504
Simoselaps anomalus	97	0.654	**0.703**	**0.718**	**0.738**	0.696	**0.704**	**0.738**	0.680
Simoselaps bertholdi	420	0.673	0.663	0.627	0.601	0.639	0.645	0.653	0.643
Strophurus ciliaris	787	0.494	0.478	0.512	0.507	0.480	0.486	0.526	0.495
Strophurus elderi	393	0.681	0.656	0.606	0.546	0.506	0.652	0.609	0.629
Strophurus intermedius	384	0.682	**0.716**	**0.704**	**0.750**	**0.708**	0.697	**0.713**	**0.718**
Strophurus jeanae	73	**0.773**	0.689	**0.717**	0.640	0.621	0.604	**0.720**	0.686
Strophurus williamsi	167	**0.781**	0.675	**0.782**	**0.729**	**0.810**	**0.803**	**0.815**	**0.806**
Suta punctata	179	0.685	**0.744**	**0.737**	**0.743**	**0.732**	**0.761**	0.676	**0.740**

TABLE B.8 - ***Continued.***

Australien		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Suta suta	586	0.484	0.530	0.459	0.540	0.491	0.484	0.536	0.562
Tiliqua multifasciata	350	0.555	0.517	0.506	0.536	0.486	0.469	0.543	0.527
Tiliqua occipitalis	393	0.651	0.679	0.657	**0.720**	0.643	0.654	**0.703**	**0.707**
Tiliqua rugosa	1928	0.695	**0.707**	**0.716**	**0.722**	**0.707**	**0.728**	**0.720**	**0.724**
Tympanocryptis centralis	93	0.550	0.539	0.621	0.684	0.539	0.656	0.481	0.668
Tympanocryptis intima	257	**0.845**	**0.842**	**0.843**	**0.807**	**0.826**	**0.776**	**0.859**	**0.856**
Tympanocryptis lineata	374	0.387	0.427	0.458	0.544	0.473	0.405	0.433	0.544
Tympanocryptis tetraporophora	556	0.641	0.649	0.654	0.635	**0.760**	0.660	**0.704**	0.683
Underwoodisaurus milii	1150	0.637	0.640	0.667	0.682	0.632	0.642	0.672	0.690
Varanus acanthurus	438	0.623	0.636	0.651	0.647	0.656	0.673	0.626	0.679
Varanus brevicauda	140	0.619	0.666	0.632	0.676	0.631	0.683	0.614	0.664
Varanus eremius	285	0.466	0.542	0.509	0.589	0.501	0.626	0.505	0.586
Varanus giganteus	214	0.593	**0.719**	0.667	**0.758**	0.619	0.665	**0.712**	**0.769**
Varanus gilleni	237	0.669	0.652	**0.703**	0.638	0.661	0.541	**0.710**	0.676
Varanus gouldii	2015	0.320	0.340	0.360	0.395	0.366	0.366	0.383	0.397
Varanus tristis	565	0.442	0.446	0.441	0.515	0.442	0.483	0.495	0.493
Varanus varius	1171	**0.821**	**0.819**	**0.806**	**0.824**	**0.873**	**0.870**	**0.827**	**0.830**
Vermicella annulata	375	**0.735**	0.652	**0.757**	0.700	0.675	**0.711**	**0.748**	**0.708**

TABLE B.8 - ***Continued.***

Caatinga		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
AMPHIBIA									
Dendropsophus nanus	128	0.445	**0.657**	**0.711**	**0.657**	**0.614**	**0.674**	**0.678**	**0.625**
Elachistocleis ovalis	60	**0.584**	0.365	**0.543**	0.366	0.308	0.372	0.442	0.410
Hypsiboas albomarginatus	69	**0.730**	**0.704**	**0.741**	**0.787**	0.410	**0.640**	**0.780**	**0.813**
Hypsiboas crepitans	161	**0.804**	**0.644**	**0.740**	**0.738**	0.474	**0.736**	**0.788**	**0.745**
Hypsiboas faber	39	**0.861**	**0.884**	**0.954**	**0.940**	**0.647**	0.000	**0.954**	**0.914**
Hypsiboas raniceps	98	**0.683**	**0.655**	**0.695**	**0.600**	**0.556**	**0.511**	**0.639**	**0.720**
Leptodactylus fuscus	184	0.354	**0.610**	**0.559**	**0.587**	0.000	0.355	**0.515**	**0.588**
Leptodactylus ocellatus	306	**0.552**	**0.655**	**0.666**	**0.640**	**0.527**	**0.618**	**0.591**	**0.656**
Lithobates palmipes	75	**0.633**	**0.514**	**0.644**	**0.704**	**0.657**	**0.720**	**0.626**	**0.791**
Physalaemus cuvieri	58	0.482	0.488	**0.546**	**0.612**	0.395	**0.573**	**0.610**	**0.673**
Pseudopaludicola mystacalis	16	0.000	**0.730**	**0.617**	**0.866**	**0.622**	0.439	**0.623**	**0.704**
Rhinella crucifer	51	**0.550**	**0.591**	**0.666**	**0.723**	**0.611**	**0.690**	**0.589**	**0.674**
Rhinella granulosus	150	**0.642**	**0.604**	**0.591**	**0.597**	0.468	0.275	**0.659**	**0.558**
Rhinella marinus	215	0.445	0.443	**0.588**	**0.571**	**0.549**	**0.594**	**0.548**	**0.572**
Rhinella schneideri	130	**0.822**	**0.638**	**0.789**	**0.649**	**0.757**	**0.574**	**0.795**	**0.692**
Scinax fuscovarius	59	**0.578**	**0.668**	**0.673**	**0.758**	**0.564**	**0.707**	**0.611**	**0.751**
Scinax ruber	201	**0.584**	**0.568**	**0.622**	**0.588**	0.435	0.445	**0.613**	**0.611**
Siphonops annulatus	20	0.000	0.127	0.461	**0.623**	**0.797**	0.428	**0.520**	**0.531**
MAMMALIA									
Alouatta caraya	55	**0.661**	**0.901**	**0.673**	**0.863**	**0.629**	**0.778**	**0.741**	**0.955**
Callithrix jacchus	24	**0.522**	0.157	**0.648**	**0.581**	0.385	**0.534**	**0.554**	0.422

TABLE B.8 - ***Continued.***

Caatinga		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Calomys callosus	161	**0.693**	**0.777**	**0.683**	**0.765**	**0.681**	**0.752**	**0.661**	**0.773**
Cerdocyon thous	178	**0.674**	**0.781**	**0.724**	**0.792**	0.439	**0.745**	**0.698**	**0.740**
Cerradomys subflavus	47	0.354	0.418	0.376	**0.632**	0.406	0.300	**0.507**	**0.734**
Coendou prehensilis	61	0.434	0.399	**0.570**	**0.531**	0.368	0.333	0.424	**0.504**
Conepatus semistriatus	20	0.451	**0.739**	0.451	**0.912**	**0.580**	**0.838**	**0.732**	**0.920**
Cuniculus paca	248	**0.571**	**0.630**	**0.666**	**0.676**	**0.529**	**0.555**	**0.600**	**0.657**
Didelphis albiventris	208	**0.706**	**0.648**	**0.725**	**0.717**	**0.678**	0.275	**0.745**	**0.673**
Euphractus sexcinctus	43	0.452	0.000	**0.566**	**0.721**	**0.687**	**0.644**	**0.568**	**0.674**
Gracilinanus agilis	28	**0.644**	**0.820**	**0.694**	**0.789**	0.295	0.069	**0.666**	**0.747**
Leopardus pardalis	54	**0.576**	**0.570**	**0.757**	**0.679**	0.425	0.362	**0.838**	**0.675**
Leopardus tigrinus	38	**0.810**	**0.936**	**0.828**	**0.943**	**0.682**	0.000	**0.830**	**0.953**
Mazama gouazoubira	27	0.241	0.000	0.220	0.420	**0.702**	0.155	**0.523**	**0.584**
Monodelphis domestica	30	**0.736**	**0.716**	**0.653**	**0.831**	**0.503**	**0.831**	**0.840**	**0.804**
Myrmecophaga tridactyla	61	0.356	0.283	0.369	0.440	0.056	0.000	0.375	0.450
Necromys lasiurus	91	0.240	**0.604**	**0.787**	**0.721**	**0.577**	0.429	**0.692**	**0.597**
Ozotoceros bezoarticus	18	0.500	**0.632**	0.200	**0.690**	0.265	**0.626**	**0.688**	**0.672**
Panthera onca	70	0.219	0.030	**0.549**	0.175	0.260	0.002	**0.518**	0.120
Pecari tajacu	111	0.448	**0.525**	0.498	**0.560**	0.214	0.397	0.433	0.485
Procyon cancrivorus	82	**0.643**	**0.716**	**0.642**	**0.666**	**0.517**	**0.596**	**0.642**	**0.596**
Puma concolor	274	**0.607**	**0.637**	**0.691**	**0.711**	**0.550**	**0.604**	**0.624**	**0.702**
Puma yagouaroundi	73	0.269	0.454	0.404	0.488	0.341	0.429	0.426	0.339
Tayassu pecari	99	0.329	0.296	**0.626**	**0.541**	0.177	**0.502**	**0.609**	**0.595**

TABLE B.8 - ***Continued.***

Caatinga		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Calomys callosus	161	**0.693**	**0.777**	**0.683**	**0.765**	**0.681**	**0.752**	**0.661**	**0.773**
Cerdocyon thous	178	**0.674**	**0.781**	**0.724**	**0.792**	0.439	**0.745**	**0.698**	**0.740**
Cerradomys subflavus	47	0.354	0.418	0.376	**0.632**	0.406	0.300	**0.507**	**0.734**
Coendou prehensilis	61	0.434	0.399	**0.570**	**0.531**	0.368	0.333	0.424	**0.504**
Conepatus semistriatus	20	0.451	**0.739**	0.451	**0.912**	**0.580**	**0.838**	**0.732**	**0.920**
Cuniculus paca	248	**0.571**	**0.630**	**0.666**	**0.676**	**0.529**	**0.555**	**0.600**	**0.657**
Didelphis albiventris	208	**0.706**	**0.648**	**0.725**	**0.717**	**0.678**	0.275	**0.745**	**0.673**
Euphractus sexcinctus	43	0.452	0.000	**0.566**	**0.721**	**0.687**	**0.644**	**0.568**	**0.674**
Gracilinanus agilis	28	**0.644**	**0.820**	**0.694**	**0.789**	0.295	0.069	**0.666**	**0.747**
Leopardus pardalis	54	**0.576**	**0.570**	**0.757**	**0.679**	0.425	0.362	**0.838**	**0.675**
Leopardus tigrinus	38	**0.810**	**0.936**	**0.828**	**0.943**	**0.682**	0.000	**0.830**	**0.953**
Mazama gouazoubira	27	0.241	0.000	0.220	0.420	**0.702**	0.155	**0.523**	**0.584**
Monodelphis domestica	30	**0.736**	**0.716**	**0.653**	**0.831**	**0.503**	**0.831**	**0.840**	**0.804**
Myrmecophaga tridactyla	61	0.356	0.283	0.369	0.440	0.056	0.000	0.375	0.450
Necromys lasiurus	91	0.240	**0.604**	**0.787**	**0.721**	**0.577**	0.429	**0.692**	**0.597**
Ozotoceros bezoarticus	18	0.500	**0.632**	0.200	**0.690**	0.265	**0.626**	**0.688**	**0.672**
Panthera onca	70	0.219	0.030	**0.549**	0.175	0.260	0.002	**0.518**	0.120
Pecari tajacu	111	0.448	**0.525**	0.498	**0.560**	0.214	0.397	0.433	0.485
Procyon cancrivorus	82	**0.643**	**0.716**	**0.642**	**0.666**	**0.517**	**0.596**	**0.642**	**0.596**
Puma concolor	274	**0.607**	**0.637**	**0.691**	**0.711**	**0.550**	**0.604**	**0.624**	**0.702**
Puma yagouaroundi	73	0.269	0.454	0.404	0.488	0.341	0.429	0.426	0.339
Tayassu pecari	99	0.329	0.296	**0.626**	**0.541**	0.177	**0.502**	**0.609**	**0.595**

TABLE B.8 - ***Continued.***

Caatinga		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Thrichomys apereoides	19	**0.517**	**0.807**	0.387	**0.660**	0.082	**0.585**	**0.655**	**0.820**
REPTILIA									
Ameiva ameiva	160	0.285	**0.556**	0.342	**0.537**	0.275	0.391	0.366	**0.579**
Amphisbaena alba	24	0.345	0.459	0.493	**0.556**	**0.538**	0.435	0.270	**0.501**
Crotalus durissus	48	0.410	0.482	0.486	**0.572**	0.453	**0.514**	0.444	**0.547**
Iguana iguana	54	**0.631**	0.250	**0.589**	**0.644**	**0.600**	**0.599**	**0.589**	0.468
Liophis poecilogyrus	99	**0.552**	**0.646**	**0.598**	**0.620**	0.208	**0.618**	**0.602**	**0.636**
Oxybelis aeneus	77	**0.781**	**0.812**	**0.813**	**0.756**	**0.774**	0.500	**0.823**	**0.848**
Oxyrhopus trigeminus	23	0.472	**0.717**	**0.703**	**0.745**	**0.720**	0.359	**0.677**	**0.911**
Philodryas olfersii	46	0.454	**0.652**	**0.530**	**0.572**	0.000	**0.517**	**0.547**	0.468
Polychrus acutirostris	20	0.000	0.232	0.352	**0.724**	**0.682**	0.240	**0.535**	**0.617**
Salvator rufescens	23	**0.902**	**0.695**	**0.752**	**0.612**	**0.673**	**0.503**	**0.892**	**0.621**
Tropidurus hispidus	51	0.447	**0.647**	**0.510**	**0.593**	0.361	**0.574**	**0.672**	0.498
Tropidurus torquatus	29	0.296	0.401	0.467	**0.511**	**0.664**	0.121	**0.683**	0.478
Xenodon merremi	160	**0.722**	**0.674**	**0.633**	**0.668**	**0.614**	0.000	**0.666**	**0.619**

TABLE B.8 - ***Continued.***

SW Africa		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
AMPHIBIA									
Amietia angolensis	312	**0.843**	**0.797**	**0.838**	**0.835**	0.676	**0.826**	**0.843**	**0.832**
Amietia fuscigula	109	**0.858**	**0.915**	**0.819**	**0.839**	**0.847**	**0.857**	**0.880**	**0.870**
Amietophrynus gutturalis	164	**0.718**	**0.729**	**0.724**	**0.786**	**0.702**	**0.737**	**0.712**	**0.758**
Amietophrynus maculatus	145	0.674	0.611	0.558	0.620	0.589	0.522	0.547	0.640
Amietophrynus rangeri	15	**0.951**	**0.952**	**0.952**	**0.953**	0.618	0.644	**0.952**	**0.952**
Breviceps adspersus	45	0.687	0.600	**0.862**	**0.846**	**0.724**	0.582	**0.872**	0.663
Cacosternum boettgeri	47	**0.843**	**0.910**	**0.827**	**0.867**	0.606	**0.842**	**0.842**	**0.948**
Kassina senegalensis	91	0.625	0.527	0.665	0.568	0.491	0.508	0.620	0.603
Phrynobatrachus natalensis	104	0.556	0.497	0.523	0.447	0.562	0.381	0.539	0.531
Phrynomantis annectens	22	**0.718**	**0.952**	**0.954**	**0.953**	0.468	**0.968**	**0.953**	**0.952**
Pyxicephalus adspersus	27	**0.848**	0.502	**0.894**	**0.840**	**0.885**	0.119	**0.857**	**0.870**
Tomopterna cryptotis	71	0.592	**0.781**	**0.785**	**0.753**	0.681	**0.723**	**0.730**	**0.708**
Tomopterna delalandii	15	**0.846**	0.540	**0.885**	0.261	0.623	0.134	**0.707**	0.680
Vandijkophrynus gariepensis	27	**0.964**	**0.964**	**0.772**	**0.771**	0.000	**0.963**	**0.953**	**0.954**
Xenopus laevis	69	**0.829**	**0.769**	**0.831**	**0.794**	**0.783**	0.696	**0.809**	**0.777**
MAMMALIA									
Acinonyx jubatus	23	**0.864**	**0.920**	0.650	**0.914**	**0.902**	0.612	**0.788**	**0.849**
Aethomys chrysophilus	191	**0.786**	**0.804**	**0.799**	**0.753**	**0.818**	**0.830**	**0.872**	**0.807**
Aethomys namaquensis	232	**0.817**	**0.823**	**0.821**	**0.838**	**0.834**	**0.838**	**0.820**	**0.826**
Alcelaphus buselaphus	73	0.649	0.613	**0.727**	0.692	0.343	0.437	**0.743**	0.688
Antidorcas marsupialis	30	**0.776**	**0.953**	**0.780**	**0.905**	0.000	**0.920**	**0.940**	**0.916**

TABLE B.8 - ***Continued.***

SW Africa		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Atilax paludinosus	38	0.679	0.493	0.587	0.578	0.591	0.342	0.610	0.620
Canis mesomelas	74	**0.849**	**0.752**	**0.779**	0.660	0.696	**0.747**	**0.862**	**0.706**
Caracal caracal	23	**0.860**	0.547	**0.721**	0.633	0.688	0.000	**0.752**	**0.752**
Chlorocebus pygerythrus	33	0.630	**0.724**	**0.738**	**0.795**	0.241	0.000	**0.885**	**0.857**
Connochaetes gnou	20	**0.729**	**0.949**	0.656	**0.956**	0.491	**0.961**	**0.873**	**0.952**
Crocidura cyanea	42	**0.770**	**0.804**	**0.763**	**0.860**	**0.814**	**0.821**	**0.748**	**0.946**
Crocuta crocuta	101	0.556	0.626	0.678	0.674	0.413	0.617	0.628	0.620
Cryptomys hottentotus	68	0.563	**0.744**	**0.742**	**0.796**	0.647	0.656	**0.744**	**0.818**
Cynictis penicillata	44	**0.723**	**0.912**	**0.708**	**0.938**	0.490	**0.822**	**0.726**	**0.920**
Dendromus melanotis	68	0.676	**0.713**	0.572	0.658	0.668	0.604	0.663	**0.739**
Desmodillus auricularis	106	0.572	**0.929**	**0.884**	**0.926**	0.000	0.000	**0.912**	**0.921**
Diceros bicornis	76	0.566	**0.799**	**0.801**	**0.922**	**0.717**	**0.864**	**0.756**	**0.884**
Elephantulus intufi	70	**0.885**	**0.806**	**0.880**	**0.878**	**0.817**	0.671	**0.883**	**0.885**
Elephantulus myurus	49	**0.845**	**0.847**	**0.844**	**0.924**	**0.821**	0.470	**0.923**	**0.913**
Elephantulus rupestris	56	0.570	**0.864**	0.589	**0.857**	0.407	**0.758**	0.695	**0.864**
Equus quagga	93	0.693	**0.708**	**0.713**	**0.804**	0.569	0.481	**0.712**	**0.749**
Felis silvestris	56	0.164	0.509	0.435	0.525	0.449	0.363	0.331	0.560
Funisciurus congicus	67	**0.805**	**0.834**	**0.845**	**0.865**	0.616	**0.789**	**0.753**	**0.774**
Genetta genetta	27	0.442	0.419	0.452	0.353	0.055	0.454	0.554	0.323
Gerbilliscus brantsii	27	**0.943**	**0.937**	**0.939**	**0.739**	**0.951**	**0.940**	**0.893**	**0.915**
Gerbilliscus leucogaster	143	**0.720**	**0.753**	**0.733**	**0.752**	0.692	0.695	**0.722**	**0.751**
Gerbillurus paeba	152	**0.859**	**0.926**	**0.889**	**0.913**	**0.853**	**0.775**	**0.912**	**0.905**

TABLE B.8 - ***Continued.***

SW Africa		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Giraffa camelopardalis	50	0.594	0.526	0.688	**0.716**	0.376	0.000	**0.739**	0.672
Helogale parvula	16	0.651	**0.841**	**0.826**	**0.844**	0.264	0.613	**0.724**	**0.732**
Herpestes pulverulentus	18	**0.953**	**0.861**	**0.952**	**0.926**	0.680	**0.704**	**0.952**	**0.928**
Herpestes sanguineus	85	0.391	0.373	0.468	0.445	0.388	0.415	0.479	0.409
Hippopotamus amphibius	105	**0.735**	0.679	0.619	**0.738**	0.699	0.564	**0.706**	0.657
Hyaena brunnea	19	**0.885**	**0.924**	**0.702**	**0.904**	0.000	0.000	**0.906**	**0.893**
Hystrix africaeaustralis	57	0.645	**0.853**	0.633	**0.772**	0.560	0.668	0.533	**0.870**
Ictonyx striatus	23	0.676	**0.903**	**0.824**	**0.874**	**0.725**	0.614	0.540	**0.760**
Lepus capensis	195	0.603	0.573	0.591	0.520	0.553	0.391	0.561	0.505
Lepus saxatilis	54	**0.857**	**0.864**	**0.759**	**0.816**	0.619	**0.729**	**0.851**	**0.835**
Loxodonta africana	87	0.615	0.455	0.563	0.600	0.383	0.546	0.590	0.553
Macroscelides proboscideus	32	**0.789**	**0.859**	**0.786**	**0.953**	0.000	0.620	**0.902**	**0.953**
Malacothrix typica	32	**0.953**	**0.756**	**0.909**	0.617	0.622	0.000	**0.930**	**0.891**
Mastomys natalensis	694	0.531	0.503	0.517	0.546	0.535	0.507	0.595	0.566
Mus indutus	71	0.657	**0.770**	**0.739**	**0.849**	**0.757**	**0.780**	**0.841**	**0.833**
Mus minutoides	139	0.613	0.652	0.584	0.639	0.642	0.571	0.611	0.633
Myotomys unisulcatus	16	0.327	**0.980**	**0.961**	0.618	**0.966**	**0.982**	**0.953**	**0.952**
Mystromys albicaudatus	18	**0.916**	0.241	**0.961**	**0.953**	0.694	**0.727**	**0.952**	**0.701**
Oreotragus oreotragus	32	**0.761**	0.000	**0.845**	0.595	**0.754**	0.591	**0.924**	0.615
Orycteropus afer	44	0.669	0.582	0.534	0.609	0.523	0.667	0.621	0.589
Oryx gazella	38	**0.704**	0.516	**0.814**	0.686	0.081	0.458	**0.846**	0.662
Otocyon megalotis	31	**0.746**	**0.780**	**0.757**	**0.868**	0.606	**0.729**	**0.780**	**0.918**

TABLE B.8 - ***Continued.***

SW Africa		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Otomys irroratus	100	**0.896**	**0.886**	**0.860**	**0.869**	**0.840**	**0.796**	**0.885**	**0.745**
Panthera leo	76	0.649	0.675	**0.734**	**0.760**	0.000	**0.803**	**0.797**	**0.787**
Papio ursinus	33	**0.914**	**0.936**	**0.809**	**0.953**	**0.789**	**0.948**	**0.865**	**0.953**
Parotomys brantsii	16	0.306	**0.951**	**0.958**	**0.956**	**0.981**	0.644	**0.951**	**0.951**
Pedetes capensis	117	**0.823**	**0.824**	**0.787**	**0.863**	**0.708**	**0.855**	**0.796**	**0.832**
Petromus typicus	23	**0.902**	**0.953**	**0.754**	**0.958**	0.572	0.570	**0.953**	**0.953**
Petromyscus collinus	33	**0.956**	0.621	**0.954**	**0.954**	**0.825**	**0.817**	**0.954**	**0.953**
Phacochoerus africanus	42	0.442	0.514	0.684	0.619	0.422	0.436	0.578	0.644
Procavia capensis	100	**0.810**	**0.750**	**0.820**	0.700	**0.722**	0.000	**0.800**	**0.772**
Proteles cristata	25	**0.849**	**0.881**	0.687	**0.936**	0.000	**0.878**	**0.857**	**0.940**
Raphicerus campestris	75	0.694	**0.829**	0.585	**0.829**	0.474	**0.733**	**0.764**	**0.833**
Redunca arundinum	31	**0.820**	**0.846**	0.664	**0.835**	**0.731**	**0.886**	0.691	**0.750**
Redunca fulvorufula	19	**0.950**	**0.842**	**0.934**	**0.952**	0.000	**0.926**	**0.952**	**0.952**
Rhabdomys pumilio	250	**0.777**	**0.828**	**0.804**	**0.832**	**0.785**	**0.797**	**0.825**	**0.820**
Saccostomus campestris	196	**0.761**	**0.813**	**0.739**	**0.780**	0.673	**0.785**	**0.767**	**0.785**
Steatomys pratensis	94	**0.768**	**0.738**	**0.756**	**0.790**	0.690	0.577	**0.790**	**0.744**
Suricata suricatta	15	**0.948**	**0.938**	0.601	0.618	0.614	**0.954**	**0.952**	**0.766**
Syncerus caffer	85	0.621	0.579	0.510	0.674	0.691	0.623	0.514	0.540
Thallomys nigricauda	36	0.405	**0.914**	**0.782**	**0.936**	0.668	**0.956**	**0.796**	**0.937**
Tragelaphus oryx	55	0.657	0.642	**0.711**	**0.743**	0.592	0.473	0.686	**0.790**
Vulpes chama	32	0.557	0.617	**0.735**	**0.758**	0.619	0.000	**0.717**	0.694
Xerus inauris	48	**0.905**	**0.930**	**0.934**	**0.954**	**0.854**	**0.913**	**0.943**	**0.954**

TABLE B.8 - ***Continued.***

SW Africa		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
REPTILIA									
Acanthocercus atricollis	211	**0.819**	**0.771**	**0.812**	**0.796**	**0.720**	0.638	**0.788**	**0.804**
Acontias gracilicauda	27	**0.748**	0.515	0.570	**0.953**	0.572	**0.756**	**0.953**	**0.952**
Acontias meleagris	30	**0.795**	**0.784**	**0.942**	**0.786**	0.629	0.312	**0.953**	**0.953**
Acontias percivali	22	**0.872**	**0.904**	**0.936**	**0.911**	0.224	**0.908**	**0.952**	**0.930**
Agama aculeata	227	**0.806**	**0.836**	**0.811**	**0.852**	**0.768**	**0.795**	**0.847**	**0.886**
Agama anchietae	160	**0.885**	**0.907**	**0.952**	**0.869**	**0.879**	**0.853**	**0.933**	**0.886**
Agama atra	210	**0.890**	**0.790**	**0.875**	**0.925**	**0.906**	**0.875**	**0.899**	**0.914**
Agama hispida	115	**0.834**	**0.894**	**0.867**	**0.823**	**0.770**	0.642	**0.902**	**0.850**
Aspidelaps lubricus	36	**0.814**	**0.811**	**0.916**	**0.789**	0.667	**0.810**	**0.930**	**0.905**
Aspidelaps scutatus	21	**0.895**	**0.892**	**0.932**	0.651	**0.702**	0.000	**0.952**	**0.834**
Bitis arietans	288	0.650	**0.750**	0.696	**0.752**	0.641	**0.733**	0.695	**0.751**
Bitis caudalis	156	**0.865**	**0.877**	**0.930**	**0.879**	**0.720**	**0.850**	**0.927**	**0.900**
Boaedon fuliginosus	139	0.669	0.570	**0.709**	0.574	0.568	0.443	**0.705**	0.580
Chamaeleo dilepis	221	0.633	**0.738**	0.660	**0.756**	0.568	**0.819**	0.645	**0.792**
Chamaeleo namaquensis	48	0.690	**0.957**	**0.776**	**0.956**	0.695	**0.983**	**0.856**	**0.956**
Chamaesaura anguina	32	**0.811**	**0.816**	**0.790**	**0.954**	**0.803**	**0.909**	**0.882**	**0.953**
Chondrodactylus angulifer	108	**0.900**	**0.901**	**0.908**	**0.902**	**0.871**	0.000	**0.916**	**0.915**
Chondrodactylus bibronii	102	**0.903**	**0.883**	**0.820**	**0.838**	**0.751**	0.000	**0.882**	**0.894**
Chondrodactylus fitzsimonsi	42	**0.754**	0.552	**0.955**	**0.958**	0.622	**0.991**	**0.955**	**0.955**
Chondrodactylus turneri	123	**0.826**	**0.857**	**0.863**	**0.838**	**0.839**	**0.860**	**0.801**	**0.874**
Cordylosaurus subtessellatus	60	**0.717**	**0.956**	**0.956**	**0.952**	**0.875**	0.000	**0.941**	**0.956**

TABLE B.8 - ***Continued.***

SW Africa		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Cordylus cordylus	33	**0.832**	**0.903**	**0.818**	**0.967**	**0.933**	0.698	**0.946**	**0.954**
Dasypeltis scabra	242	0.657	0.691	**0.753**	**0.724**	0.639	0.367	**0.703**	**0.723**
Dendroaspis polylepis	83	0.677	0.687	**0.755**	0.631	0.000	0.643	**0.808**	0.687
Dipsina multimaculata	43	**0.945**	0.634	**0.949**	**0.955**	0.316	0.545	**0.886**	**0.954**
Gerrhosaurus nigrolineatus	67	0.665	**0.726**	0.571	**0.702**	0.494	0.649	0.634	**0.726**
Gerrhosaurus validus	64	**0.926**	**0.942**	**0.943**	**0.857**	0.425	**0.842**	**0.908**	**0.825**
Goggia lineata	29	**0.826**	**0.983**	**0.826**	**0.817**	**0.823**	**0.994**	**0.959**	**0.965**
Heliobolus lugubris	165	**0.898**	**0.890**	**0.883**	**0.909**	**0.875**	**0.876**	**0.872**	**0.920**
Hemachatus haemachatus	83	**0.968**	**0.749**	**0.959**	**0.899**	**0.978**	0.000	**0.958**	**0.934**
Karusasaurus jordani	25	**0.974**	**0.725**	**0.953**	**0.752**	**0.774**	**0.749**	**0.953**	**0.953**
Karusasaurus polyzonus	128	**0.962**	**0.925**	**0.923**	**0.949**	**0.967**	**0.854**	**0.962**	**0.960**
Lamprophis guttatus	27	**0.755**	**0.752**	0.551	**0.911**	**0.752**	**0.752**	**0.785**	**0.948**
Leptotyphlops scutifrons	133	0.657	**0.765**	**0.858**	**0.737**	**0.848**	**0.804**	**0.836**	**0.827**
Lycodonomorphus laevissimus	20	0.492	**0.987**	0.468	**0.708**	0.658	**0.897**	**0.942**	**0.956**
Lygodactylus bradfieldi	41	**0.786**	**0.862**	**0.817**	**0.917**	0.684	**0.820**	**0.868**	**0.954**
Lygodactylus capensis	201	**0.725**	**0.704**	**0.729**	0.662	**0.720**	**0.710**	**0.731**	0.684
Lygodactylus lawrencei	15	**0.968**	0.324	**0.956**	**0.958**	**0.993**	0.662	**0.952**	**0.952**
Lygosoma sundevalli	184	**0.713**	**0.760**	**0.739**	**0.757**	0.692	**0.712**	**0.731**	**0.718**
Megatyphlops schlegelii	61	**0.787**	**0.873**	**0.745**	**0.852**	**0.837**	**0.860**	**0.768**	**0.952**
Meroles anchietae	27	**0.979**	**0.982**	**0.954**	**0.962**	**0.794**	**0.996**	**0.953**	**0.955**
Meroles ctenodactylus	17	**0.978**	**0.986**	**0.961**	**0.965**	0.637	**0.989**	**0.952**	**0.952**
Meroles cuneirostris	42	**0.868**	**0.996**	**0.836**	**0.959**	**0.743**	**0.996**	**0.956**	**0.957**

TABLE B.8 - ***Continued.***

SW Africa		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Meroles knoxii	54	**0.885**	**0.956**	**0.798**	**0.974**	**0.956**	**0.989**	**0.957**	**0.958**
Meroles reticulatus	25	**0.787**	**0.985**	**0.982**	**0.976**	**0.985**	**0.994**	**0.965**	**0.969**
Meroles suborbitalis	34	**0.837**	**0.971**	**0.954**	**0.966**	**0.840**	**0.977**	**0.955**	**0.954**
Microacontias lineatus	28	0.697	**0.803**	**0.791**	**0.965**	0.631	**0.933**	**0.954**	**0.954**
NajaNigricollis	73	0.516	0.550	0.522	0.572	0.000	0.436	0.408	0.572
Naja nivea	21	**0.942**	**0.941**	**0.955**	**0.952**	**0.701**	**0.940**	**0.952**	**0.952**
Narudasia festiva	26	**0.981**	**0.980**	**0.976**	**0.964**	0.000	**0.789**	**0.954**	**0.956**
Nucras intertexta	59	0.392	**0.860**	0.646	**0.893**	0.000	0.644	**0.841**	**0.881**
Nucras ornata	68	**0.865**	**0.935**	**0.834**	**0.876**	**0.861**	0.632	**0.885**	**0.866**
Nucras tessellata	53	**0.770**	**0.864**	0.681	**0.864**	**0.790**	**0.854**	**0.906**	**0.928**
Pachydactylus bicolor	38	**0.844**	**0.970**	**0.838**	**0.958**	**0.736**	**0.992**	**0.834**	**0.957**
Pachydactylus carinatus	17	0.323	**0.965**	**0.990**	**0.986**	**0.994**	**0.994**	**0.954**	**0.958**
Pachydactylus haackei	15	**0.990**	**0.994**	**0.955**	**0.957**	**0.726**	**0.840**	**0.952**	**0.953**
Pachydactylus laevigatus	113	**0.925**	**0.883**	**0.917**	**0.870**	**0.917**	**0.800**	**0.917**	**0.913**
Pachydactylus maculatus	32	**0.968**	**0.975**	**0.785**	**0.786**	0.533	0.620	**0.930**	**0.930**
Pachydactylus mariquensis	43	**0.848**	**0.862**	**0.845**	**0.956**	0.535	**0.973**	**0.954**	**0.954**
Pachydactylus montanus	32	0.660	**0.984**	**0.804**	**0.793**	0.625	0.000	**0.957**	**0.962**
Pachydactylus punctatus	196	**0.917**	**0.878**	**0.892**	**0.857**	**0.904**	**0.837**	**0.901**	**0.873**
Pachydactylus purcelli	37	**0.814**	**0.972**	**0.816**	**0.958**	0.698	**0.840**	**0.954**	**0.954**
Pachydactylus rangei	53	**0.811**	**0.900**	**0.851**	**0.956**	**0.776**	**0.903**	**0.958**	**0.955**
Pachydactylus rugosus	53	**0.955**	**0.773**	**0.857**	**0.865**	**0.959**	**0.877**	**0.948**	**0.889**
Pachydactylus scherzi	26	0.599	**0.958**	**0.961**	**0.970**	**0.950**	**0.992**	**0.960**	**0.958**

TABLE B.8 - ***Continued.***

SW Africa		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Pachydactylus scutatus	24	**0.790**	**0.787**	0.555	**0.758**	**0.782**	**0.759**	**0.938**	**0.933**
Pachydactylus serval	32	**0.974**	**0.817**	**0.978**	**0.804**	**0.826**	0.000	**0.953**	**0.956**
Pachydactylus vanzyli	20	**0.990**	**0.994**	**0.990**	**0.990**	**0.996**	**0.996**	**0.957**	**0.967**
Pachydactylus weberi	59	**0.813**	**0.987**	**0.872**	**0.958**	**0.906**	**0.985**	**0.900**	**0.956**
Panaspis wahlbergii	186	**0.761**	**0.807**	**0.756**	**0.802**	0.700	**0.810**	**0.766**	**0.770**
Pedioplanis breviceps	50	**0.990**	**0.891**	**0.965**	**0.767**	**0.995**	**0.792**	**0.966**	**0.961**
Pedioplanis gaerdesi	52	**0.998**	**0.896**	**0.862**	**0.961**	**0.889**	**0.992**	**0.977**	**0.961**
Pedioplanis inornata	50	0.688	**0.964**	**0.860**	**0.966**	**0.787**	0.000	**0.955**	**0.955**
Pedioplanis lineoocellata	207	**0.907**	**0.886**	**0.887**	**0.849**	**0.750**	**0.879**	**0.904**	**0.882**
Pedioplanis namaquensis	172	**0.897**	**0.898**	**0.940**	**0.901**	**0.908**	**0.918**	**0.951**	**0.922**
Pedioplanis undata	128	**0.886**	**0.962**	**0.923**	**0.905**	**0.962**	**0.911**	**0.962**	**0.962**
Pelomedusa subrufa	116	0.479	0.548	0.618	0.612	0.535	0.477	0.612	0.621
Philothamnus semivariegatus	163	**0.758**	**0.733**	**0.702**	**0.716**	0.627	0.682	**0.724**	**0.732**
Platysaurus capensis	27	**0.957**	**0.940**	**0.984**	**0.958**	**0.982**	**0.981**	**0.954**	**0.956**
Prosymna frontalis	17	0.636	**0.951**	**0.953**	**0.960**	0.628	0.000	**0.922**	**0.952**
Psammobates tentorius	44	**0.930**	**0.974**	**0.830**	**0.956**	0.526	0.000	**0.952**	**0.954**
Psammophis leightoni	69	**0.842**	**0.797**	**0.773**	**0.854**	**0.750**	**0.882**	**0.818**	**0.853**
Psammophis notostictus	59	**0.810**	**0.876**	**0.876**	**0.922**	**0.769**	**0.963**	**0.948**	**0.956**
Psammophis sibilans	53	0.503	0.292	0.591	0.351	0.250	0.416	0.390	0.309
Psammophis subtaeniatus	85	**0.702**	**0.735**	0.695	0.675	0.643	**0.713**	0.659	**0.710**
Psammophis trigrammus	18	**0.961**	**0.962**	**0.950**	0.212	**0.910**	**0.702**	**0.952**	**0.952**
Psammophylax rhombeatus	95	**0.959**	**0.902**	**0.960**	**0.858**	**0.961**	**0.815**	**0.959**	**0.894**

TABLE B.8 - ***Continued.***

SW Africa		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Psammophylax tritaeniatus	67	0.380	0.657	0.625	**0.759**	0.585	**0.702**	0.599	**0.792**
Pseudaspis cana	128	**0.752**	**0.854**	**0.823**	**0.861**	**0.757**	**0.824**	**0.802**	**0.813**
Pseudocordylus microlepidotus	15	**0.908**	**0.872**	**0.952**	**0.952**	0.620	0.621	**0.952**	**0.952**
Ptenopus garrulus	139	**0.916**	**0.950**	**0.897**	**0.933**	**0.906**	**0.857**	**0.912**	**0.942**
Pythonodipsas carinata	19	**0.982**	**0.993**	**0.960**	**0.985**	**0.964**	**0.994**	**0.962**	**0.962**
Rhinotyphlops lalandei	52	**0.790**	**0.808**	**0.728**	**0.837**	**0.808**	**0.820**	**0.853**	**0.892**
Rhoptropus afer	74	**0.984**	**0.988**	**0.978**	**0.978**	**0.996**	**0.992**	**0.972**	**0.963**
Rhoptropus barnardi	195	**0.937**	**0.924**	**0.941**	**0.924**	**0.941**	**0.864**	**0.942**	**0.900**
Rhoptropus biporosus	22	**0.740**	**0.996**	**0.981**	**0.986**	**0.994**	**0.748**	**0.963**	**0.964**
Rhoptropus boultoni	87	**0.942**	**0.897**	**0.916**	**0.960**	**0.914**	**0.976**	**0.922**	**0.958**
Rhoptropus bradfieldi	55	0.624	**0.788**	**0.854**	**0.961**	**0.968**	**0.964**	**0.955**	**0.957**
Smaug giganteus	15	**0.951**	**0.952**	**0.974**	**0.961**	**0.988**	**0.981**	**0.951**	**0.952**
Stigmochelys pardalis	86	**0.771**	**0.860**	**0.803**	**0.841**	**0.775**	**0.837**	**0.752**	**0.894**
Telescopus beetzi	21	0.486	**0.740**	0.479	**0.957**	**0.704**	**0.735**	**0.961**	**0.953**
Telescopus semiannulatus	110	**0.796**	0.700	**0.706**	**0.788**	**0.729**	0.688	0.685	0.682
Thelotornis capensis	132	**0.706**	0.682	**0.705**	0.680	0.621	**0.724**	**0.739**	0.697
Trachylepis acutilabris	113	**0.962**	**0.962**	**0.960**	**0.874**	**0.917**	**0.970**	**0.953**	**0.963**
Trachylepis binotata	45	0.622	**0.839**	**0.854**	**0.970**	0.000	**0.871**	**0.954**	**0.955**
Trachylepis capensis	148	**0.877**	**0.852**	**0.930**	**0.843**	**0.898**	**0.740**	**0.920**	**0.856**
Trachylepis hoeschi	55	**0.997**	**0.998**	**0.970**	**0.973**	**0.994**	**0.990**	**0.980**	**0.990**
Trachylepis occidentalis	110	**0.899**	**0.945**	**0.874**	**0.914**	**0.865**	**0.929**	**0.915**	**0.961**
Trachylepis spilogaster	130	**0.902**	**0.957**	**0.839**	**0.962**	**0.890**	**0.897**	**0.906**	**0.962**

TABLE B.8 - ***Continued.***

SW Africa		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Trachylepis striata	530	**0.743**	0.681	**0.737**	**0.705**	**0.741**	0.698	**0.778**	**0.718**
Trachylepis sulcata	229	**0.919**	**0.828**	**0.904**	**0.885**	**0.914**	**0.852**	**0.928**	**0.890**
Trachylepis varia	393	**0.748**	**0.748**	**0.710**	**0.733**	**0.752**	**0.719**	**0.733**	**0.725**
Trachylepis variegata	210	**0.838**	**0.833**	**0.885**	**0.859**	**0.887**	**0.877**	**0.882**	**0.867**
Typhlacontias brevipes	18	**0.989**	**0.748**	**0.980**	**0.984**	**0.993**	**0.747**	**0.955**	**0.964**
Typhlacontias punctatissimus	15	**0.988**	0.665	**0.987**	**0.972**	**0.994**	0.664	**0.953**	**0.954**
Typhlosaurus lineatus	72	**0.826**	**0.885**	**0.830**	**0.909**	**0.813**	**0.893**	**0.885**	**0.885**
Varanus albigularis	78	**0.817**	**0.712**	**0.820**	**0.792**	**0.797**	0.577	**0.824**	**0.781**
Varanus niloticus	123	0.480	0.630	0.578	0.547	0.430	0.576	0.564	0.514
Xenocalamus bicolor	23	**0.872**	**0.904**	**0.930**	**0.940**	0.000	**0.734**	**0.856**	**0.905**

TABLE B.8 - ***Continued.***

S Europe		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
AMPHIBIA									
Alytes obstetricans	664	**0.829**	**0.847**	**0.805**	**0.824**	**0.843**	**0.861**	**0.845**	**0.848**
Bombina variegata	516	**0.709**	0.530	**0.799**	**0.780**	**0.759**	**0.765**	**0.829**	**0.757**
Bufo bufo	8145	0.638	0.640	0.610	0.618	0.683	0.661	0.650	0.641
Calotriton asper	223	**0.852**	**0.848**	**0.903**	**0.875**	**0.938**	**0.925**	**0.948**	**0.887**
Chioglossa lusitanica	133	**0.973**	**0.928**	**0.929**	**0.966**	**0.941**	**0.904**	**0.929**	**0.964**
Discoglossus galganoi	713	**0.936**	**0.872**	**0.932**	**0.958**	**0.960**	**0.970**	**0.938**	**0.966**
Discoglossus jeanneae	487	**0.880**	**0.881**	**0.895**	**0.873**	**0.895**	**0.891**	**0.892**	**0.858**
Discoglossus pictus	44	**0.794**	**0.954**	**0.741**	**0.868**	**0.889**	**0.842**	**0.861**	**0.954**
Discoglossus sardus	27	**0.997**	**0.798**	**0.965**	**0.753**	**0.991**	**0.998**	**0.969**	**0.961**
Epidalea calamita	3422	0.694	**0.713**	**0.722**	**0.713**	**0.732**	**0.744**	**0.721**	**0.717**
Hyla arborea	1849	0.266	0.630	0.654	0.662	0.693	0.692	**0.704**	**0.703**
Hyla meridionalis	815	**0.905**	**0.919**	**0.913**	**0.917**	**0.910**	**0.904**	**0.922**	**0.920**
Lissotriton boscai	735	**0.965**	**0.961**	**0.949**	**0.959**	**0.951**	**0.970**	**0.956**	**0.963**
Lissotriton helveticus	2974	**0.802**	**0.749**	**0.778**	**0.777**	**0.826**	**0.834**	**0.809**	**0.802**
Mesotriton alpestris	1058	**0.816**	0.656	**0.825**	**0.826**	**0.810**	**0.838**	**0.824**	**0.842**
Pelobates cultripes	1376	0.642	**0.890**	**0.898**	**0.882**	**0.902**	**0.923**	**0.872**	**0.876**
Pelodytes ibericus	324	**0.933**	**0.972**	**0.957**	**0.956**	**0.965**	**0.947**	**0.959**	**0.968**
Pelodytes punctatus	1124	0.680	0.656	**0.779**	**0.792**	**0.835**	**0.824**	**0.783**	**0.806**
Pelophylax perezi	3979	**0.857**	**0.886**	**0.859**	**0.875**	**0.888**	**0.891**	**0.860**	**0.881**
Pleurodeles waltl	1116	**0.877**	**0.950**	**0.935**	**0.958**	**0.944**	**0.952**	**0.936**	**0.954**
Pseudepidalea viridis	325	0.670	**0.740**	0.657	**0.706**	**0.720**	0.686	0.660	**0.722**

TABLE B.8 - ***Continued.***

S Europe		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Rana dalmatina	969	**0.794**	**0.823**	**0.823**	**0.828**	**0.831**	**0.829**	**0.817**	**0.827**
Rana iberica	445	**0.925**	**0.940**	**0.953**	**0.963**	**0.953**	**0.965**	**0.953**	**0.955**
Salamandra salamandra	7017	**0.745**	0.448	**0.746**	**0.708**	**0.770**	**0.740**	**0.765**	**0.768**
Triturus marmoratus	2494	**0.812**	**0.765**	**0.762**	**0.793**	**0.833**	**0.774**	**0.790**	**0.804**
Triturus pygmaeus	1251	**0.966**	**0.982**	**0.961**	**0.972**	**0.961**	**0.972**	**0.972**	**0.985**
MAMMALIA									
Apodemus flavicollis	1173	0.695	**0.706**	**0.747**	**0.751**	**0.731**	**0.735**	**0.728**	**0.759**
Apodemus sylvaticus	7142	**0.727**	**0.753**	**0.712**	**0.750**	**0.760**	**0.815**	**0.743**	**0.771**
Arvicola amphibius	2650	**0.740**	**0.750**	**0.750**	**0.768**	**0.788**	**0.784**	**0.764**	**0.776**
Arvicola sapidus	2120	0.571	**0.777**	**0.760**	**0.750**	**0.819**	**0.781**	**0.790**	**0.782**
Atelerix algirus	149	**0.970**	**0.969**	**0.964**	**0.927**	**0.965**	**0.930**	**0.964**	**0.931**
Canis lupus	5077	0.314	**0.723**	**0.719**	**0.703**	**0.792**	**0.739**	**0.792**	**0.790**
Capra ibex	115	**0.816**	**0.937**	**0.919**	**0.888**	**0.961**	**0.962**	**0.917**	**0.962**
Capra pyrenaica	639	**0.907**	**0.923**	**0.909**	**0.896**	**0.917**	**0.924**	**0.910**	**0.913**
Capreolus capreolus	9653	0.692	**0.701**	0.658	0.686	**0.715**	**0.741**	**0.737**	**0.754**
Castor fiber	564	0.661	0.683	**0.723**	**0.728**	**0.790**	**0.769**	**0.726**	**0.723**
Cervus elaphus	4830	0.683	**0.706**	**0.704**	**0.718**	**0.752**	**0.732**	**0.740**	**0.721**
Chionomys nivalis	203	**0.890**	**0.857**	**0.875**	**0.885**	**0.854**	**0.851**	**0.908**	**0.896**
Crocidura leucodon	463	**0.704**	**0.792**	**0.868**	**0.883**	**0.822**	**0.891**	**0.860**	**0.866**
Crocidura russula	4851	**0.795**	**0.802**	**0.753**	**0.764**	**0.859**	**0.840**	**0.791**	**0.802**
Crocidura suaveolens	369	0.685	**0.824**	**0.845**	**0.855**	**0.722**	**0.828**	**0.812**	**0.820**
Eliomys quercinus	2971	0.559	0.561	**0.773**	**0.755**	**0.803**	**0.821**	**0.801**	**0.802**

TABLE B.8 - ***Continued.***

S Europe		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Erinaceus europaeus	8295	**0.717**	0.691	**0.717**	0.699	**0.755**	**0.739**	**0.742**	**0.729**
Felis silvestris	3409	**0.760**	0.468	**0.735**	**0.735**	**0.783**	**0.779**	**0.764**	**0.772**
Galemys pyrenaicus	530	**0.878**	0.685	**0.858**	**0.868**	**0.868**	**0.876**	**0.862**	**0.876**
Glis glis	735	**0.764**	**0.811**	**0.749**	**0.748**	**0.776**	**0.785**	**0.780**	**0.760**
Lepus europaeus	3359	0.696	0.695	**0.716**	**0.731**	**0.728**	**0.783**	**0.745**	**0.764**
Lepus granatensis	2884	**0.919**	**0.918**	**0.920**	**0.921**	**0.919**	**0.921**	**0.907**	**0.910**
Lepus timidus	779	**0.833**	**0.869**	**0.817**	**0.841**	**0.833**	**0.854**	**0.822**	**0.851**
Lutra lutra	6840	0.682	**0.703**	**0.742**	**0.757**	**0.771**	**0.791**	**0.739**	**0.763**
Lynx pardinus	318	**0.907**	**0.942**	**0.915**	**0.925**	**0.912**	0.000	**0.946**	**0.929**
Marmota marmota	285	**0.807**	**0.888**	**0.917**	**0.898**	**0.940**	**0.895**	**0.923**	**0.883**
Martes foina	6089	0.653	**0.791**	**0.734**	**0.735**	**0.817**	**0.800**	**0.787**	**0.794**
Martes martes	4019	**0.707**	**0.740**	**0.725**	**0.738**	**0.767**	**0.783**	**0.767**	**0.784**
Meles meles	8249	**0.744**	**0.740**	**0.736**	**0.743**	**0.760**	**0.805**	**0.757**	**0.767**
Micromys minutus	2164	**0.813**	**0.787**	**0.810**	**0.805**	**0.832**	**0.823**	**0.823**	**0.824**
Microtus agrestis	4521	**0.751**	**0.774**	**0.732**	**0.763**	**0.764**	**0.828**	**0.766**	**0.801**
Microtus arvalis	3248	**0.760**	**0.745**	**0.719**	0.678	**0.800**	**0.796**	**0.790**	**0.777**
Microtus cabrerae	270	**0.901**	**0.941**	**0.901**	**0.923**	**0.914**	**0.915**	**0.896**	**0.940**
Microtus duodecimcostatus	2057	**0.861**	**0.874**	**0.851**	**0.874**	**0.882**	**0.894**	**0.835**	**0.860**
Microtus gerbei	176	**0.861**	**0.941**	**0.886**	**0.934**	**0.942**	**0.950**	**0.918**	**0.961**
Microtus lusitanicus	930	**0.791**	**0.832**	**0.904**	**0.884**	**0.926**	**0.925**	**0.900**	**0.897**
Microtus subterraneus	60	0.443	0.588	0.612	0.667	0.620	**0.862**	**0.727**	0.594
Muscardinus avellanarius	5503	**0.821**	**0.844**	**0.773**	**0.820**	**0.830**	**0.839**	**0.810**	**0.826**

TABLE B.8 - ***Continued.***

S Europe		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Mus musculus	3024	**0.734**	**0.731**	**0.736**	**0.728**	**0.762**	**0.746**	**0.741**	**0.737**
Mus spretus	1113	**0.894**	**0.892**	**0.883**	**0.888**	**0.893**	**0.901**	**0.878**	**0.878**
Mustela erminea	4699	0.560	**0.778**	**0.786**	**0.760**	**0.831**	**0.801**	**0.820**	**0.796**
Mustela lutreola	381	**0.930**	**0.795**	**0.875**	**0.852**	**0.877**	**0.867**	**0.890**	**0.876**
Mustela nivalis	7867	0.677	0.693	0.677	0.687	**0.722**	**0.747**	**0.716**	**0.728**
Mustela putorius	5268	**0.734**	0.683	**0.727**	**0.749**	**0.779**	**0.764**	**0.734**	**0.766**
Myodes glareolus	3904	**0.735**	**0.726**	**0.725**	**0.728**	**0.753**	**0.786**	**0.760**	**0.759**
Neomys anomalus	780	0.612	0.603	**0.821**	**0.781**	**0.834**	**0.820**	**0.786**	**0.796**
Neomys fodiens	2182	**0.776**	**0.758**	**0.777**	**0.753**	**0.765**	**0.823**	**0.801**	**0.771**
Oryctolagus cuniculus	9174	**0.766**	**0.761**	**0.790**	**0.771**	**0.806**	**0.781**	**0.779**	**0.777**
Ovis aries	391	**0.821**	**0.762**	**0.874**	**0.854**	**0.788**	**0.825**	**0.842**	**0.860**
Rattus rattus	1675	0.680	**0.705**	0.687	**0.716**	**0.708**	**0.757**	**0.712**	**0.716**
Rupicapra pyrenaica	226	**0.939**	**0.807**	**0.920**	**0.950**	**0.971**	**0.945**	**0.906**	**0.939**
Rupicapra rupicapra	592	**0.837**	**0.932**	**0.878**	**0.893**	**0.883**	**0.920**	**0.889**	**0.908**
Sciurus vulgaris	6234	0.689	**0.702**	0.661	0.683	**0.724**	**0.732**	**0.715**	**0.727**
Sorex araneus	3060	**0.764**	**0.748**	**0.748**	**0.738**	**0.803**	**0.803**	**0.777**	**0.770**
Sorex coronatus	1749	**0.854**	**0.739**	**0.842**	**0.839**	**0.873**	**0.871**	**0.856**	**0.860**
Sorex granarius	154	**0.936**	**0.977**	**0.926**	**0.956**	0.000	**0.965**	**0.965**	**0.959**
Sorex minutus	2957	**0.763**	**0.760**	**0.745**	**0.755**	**0.783**	**0.781**	**0.767**	**0.784**
Suncus etruscus	895	**0.834**	**0.849**	**0.803**	**0.808**	**0.822**	0.000	**0.822**	**0.826**
Sus scrofa	8852	0.249	0.523	**0.702**	**0.708**	**0.746**	**0.816**	**0.758**	**0.791**
Talpa europaea	5655	**0.768**	**0.768**	**0.742**	**0.750**	**0.767**	**0.800**	**0.771**	**0.787**

TABLE B.8 - ***Continued.***

S Europe		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Talpa occidentalis	880	**0.928**	**0.866**	**0.911**	**0.925**	**0.946**	**0.917**	**0.921**	**0.931**
Vulpes vulpes	11131	**0.710**	0.699	0.677	0.652	**0.761**	**0.743**	**0.743**	**0.721**
REPTILIA									
Acanthodactylus erythrurus	600	**0.949**	**0.923**	**0.945**	**0.907**	**0.956**	**0.918**	**0.951**	**0.909**
Algyroides marchi	26	**0.990**	**0.999**	**0.973**	**0.984**	**0.994**	0.003	**0.970**	**0.973**
Anguis fragilis	4231	0.627	0.611	0.589	0.587	0.616	0.642	0.629	0.629
Blanus cinereus	1166	**0.946**	**0.950**	**0.948**	**0.944**	**0.942**	**0.952**	**0.940**	**0.956**
Chalcides bedriagai	495	**0.916**	**0.911**	**0.901**	**0.915**	**0.917**	**0.928**	**0.913**	**0.915**
Chalcides striatus	1010	**0.874**	**0.872**	**0.865**	**0.845**	**0.907**	**0.904**	**0.835**	**0.854**
Coronella austriaca	1362	0.625	0.620	0.653	0.662	0.689	0.670	0.651	0.680
Coronella girondica	1441	**0.830**	**0.813**	**0.814**	**0.812**	**0.884**	**0.859**	**0.841**	**0.826**
Emys orbicularis	742	0.663	0.660	**0.712**	**0.721**	0.000	0.694	**0.708**	0.689
Hemidactylus turcicus	478	**0.950**	**0.930**	**0.928**	**0.949**	**0.893**	**0.948**	**0.933**	**0.954**
Hemorrhois hippocrepis	928	**0.935**	**0.913**	**0.929**	**0.928**	**0.918**	**0.938**	**0.941**	**0.912**
Hierophis viridiflavus	758	**0.829**	**0.896**	**0.857**	**0.886**	**0.868**	**0.900**	**0.863**	**0.888**
Iberolacerta cyreni	161	**0.966**	**0.919**	**0.966**	**0.965**	**0.965**	**0.965**	**0.965**	**0.966**
Lacerta agilis	959	**0.706**	**0.707**	0.648	0.678	**0.703**	**0.750**	0.697	0.695
Lacerta bilineata	461	**0.718**	**0.868**	**0.811**	**0.826**	**0.836**	**0.898**	**0.862**	**0.869**
Lacerta schreiberi	510	**0.946**	**0.909**	**0.967**	**0.943**	**0.978**	**0.940**	**0.966**	**0.947**
Lacerta viridis	1037	**0.852**	**0.706**	**0.831**	**0.844**	**0.889**	**0.837**	**0.859**	**0.840**
Macroprotodon brevis	411	**0.976**	**0.966**	**0.966**	**0.949**	**0.976**	**0.949**	**0.982**	**0.962**
Malpolon monspessulanus	2558	**0.855**	**0.874**	**0.844**	**0.875**	**0.854**	**0.903**	**0.849**	**0.884**

TABLE B.8 - ***Continued.***

S Europe		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Mauremys leprosa	1271	**0.917**	**0.909**	**0.922**	**0.921**	**0.935**	**0.942**	**0.913**	**0.915**
Natrix maura	3321	**0.820**	**0.797**	**0.790**	**0.793**	**0.831**	**0.850**	**0.817**	**0.805**
Natrix natrix	4646	0.592	0.619	0.579	0.609	0.621	0.644	0.620	0.628
Podarcis bocagei	293	**0.922**	**0.952**	**0.943**	**0.943**	**0.961**	**0.958**	**0.961**	**0.943**
Podarcis carbonelli	16	0.333	**0.986**	0.652	**0.978**	0.545	**0.984**	0.631	**0.952**
Podarcis hispanicus	4639	0.681	**0.789**	**0.771**	**0.778**	**0.824**	**0.805**	**0.801**	**0.794**
Podarcis tiliguerta	31	**0.827**	**0.996**	**0.812**	**0.984**	**0.956**	**0.962**	**0.958**	**0.972**
Psammodromus hispanicus	1198	**0.884**	**0.904**	**0.885**	**0.913**	**0.913**	**0.931**	**0.889**	**0.898**
Rhinechis scalaris	2258	**0.882**	**0.878**	**0.872**	**0.871**	**0.892**	**0.885**	**0.869**	**0.877**
Tarentola mauritanica	1800	**0.914**	**0.911**	**0.901**	**0.901**	**0.917**	**0.911**	**0.915**	**0.914**
Testudo graeca	35	0.527	**0.810**	**0.741**	**0.810**	0.560	0.000	**0.709**	**0.810**
Testudo hermanni	40	**0.851**	**0.872**	**0.954**	**0.803**	**0.903**	**0.828**	**0.937**	**0.921**
Timon lepidus	3385	**0.739**	**0.866**	**0.852**	**0.867**	**0.877**	**0.889**	**0.854**	**0.858**
Vipera aspis	1281	**0.846**	**0.852**	**0.814**	**0.782**	**0.872**	**0.897**	**0.847**	**0.827**
Vipera latastei	816	**0.746**	**0.749**	**0.869**	**0.900**	**0.904**	**0.913**	**0.887**	**0.901**
Vipera ursinii	24	**0.729**	0.622	**0.818**	**0.702**	**0.956**	**0.955**	**0.952**	**0.930**
Zamenis longissimus	648	0.684	**0.815**	**0.839**	**0.821**	**0.831**	**0.834**	**0.821**	**0.816**
Zootoca vivipara	1070	0.694	**0.708**	0.674	**0.710**	0.652	**0.721**	0.689	**0.706**

TABLE B.8 - ***Continued.***

W.S. Savanna		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
AMPHIBIA									
Afrixalus dorsalis	27	**0.718**	0.151	**0.878**	**0.809**	**0.752**	0.451	**0.953**	**0.852**
Amietophrynus maculatus	194	0.679	0.688	0.655	**0.776**	0.631	0.693	**0.709**	**0.749**
Amietophrynus regularis	236	0.485	0.472	0.621	0.566	0.630	0.515	0.583	0.667
Bufo xeros	105	0.698	**0.746**	**0.747**	**0.823**	**0.737**	0.644	**0.756**	**0.795**
Hemisus guineensis	29	0.550	0.550	0.642	0.383	0.400	0.268	0.631	0.498
Hemisus marmoratus	75	**0.744**	0.672	**0.830**	**0.813**	0.669	0.636	**0.801**	**0.840**
Hildebrandtia ornata	18	0.572	0.000	**0.768**	0.308	0.439	0.000	**0.927**	0.510
Hoplobatrachus occipitalis	113	**0.993**	**0.980**	**0.964**	**0.974**	**0.993**	**0.994**	**0.975**	**0.956**
Hylarana galamensis	18	**0.838**	**0.856**	0.691	0.540	0.332	0.610	**0.850**	**0.853**
Hyperolius concolor	25	0.576	0.555	**0.930**	**0.867**	**0.752**	**0.880**	**0.953**	**0.752**
Kassina senegalensis	218	0.583	**0.714**	0.604	**0.704**	0.488	0.000	0.591	**0.723**
Leptopelis viridis	20	0.554	**0.702**	**0.748**	**0.702**	**0.966**	0.664	0.692	**0.702**
Phrynobatrachus latifrons	30	0.654	0.619	0.619	0.604	0.676	0.651	**0.836**	**0.873**
Phrynobatrachus natalensis	287	**0.731**	0.654	**0.707**	0.656	**0.724**	0.660	0.688	0.682
Ptychadena sp.	367	0.645	0.561	0.665	0.613	0.523	0.522	0.688	0.611
MAMMALIA									
Alcelaphus buselaphus	74	0.551	0.614	0.674	0.688	0.397	0.481	0.638	0.668
Anomalurus beecrofti	55	**0.888**	**0.723**	**0.817**	**0.732**	0.536	0.000	**0.880**	**0.716**
Arvicanthis niloticus	336	**0.734**	**0.701**	0.688	0.678	0.590	0.501	0.654	**0.707**
Atelerix albiventris	63	0.656	0.619	0.642	**0.797**	0.640	0.645	0.685	**0.785**
Canis aureus	65	0.337	0.694	0.590	**0.743**	0.603	0.416	0.498	**0.759**

TABLE B.8 - ***Continued.***

W.S. Savanna		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Cephalophus niger	22	**0.860**	**0.702**	**0.953**	**0.925**	**0.941**	**0.848**	**0.953**	**0.953**
Cricetomys gambianus	225	0.642	0.663	0.598	0.619	0.574	0.584	0.638	0.697
Crocidura fuscomurina	42	0.344	0.618	0.397	0.601	0.212	0.421	0.486	0.652
Crocidura olivieri	134	0.665	0.676	0.605	0.675	0.647	0.643	0.619	0.688
Crocidura poensis	34	**0.735**	**0.797**	**0.941**	**0.914**	**0.747**	**0.904**	**0.941**	**0.911**
Crossarchus obscurus	21	0.429	**0.950**	**0.702**	**0.876**	0.450	**0.961**	**0.952**	**0.952**
Dasymys rufulus	46	**0.902**	**0.891**	**0.805**	**0.821**	0.669	**0.767**	**0.859**	**0.886**
Erythrocebus patas	31	0.547	**0.891**	**0.744**	**0.827**	0.660	**0.804**	**0.719**	**0.832**
Felis silvestris	56	0.164	0.272	0.440	0.547	0.442	0.547	0.331	0.569
Felovia vae	54	**0.949**	**0.983**	**0.965**	**0.966**	**0.988**	**0.985**	**0.956**	**0.958**
Funisciurus pyrropus	93	**0.865**	**0.755**	**0.837**	**0.794**	**0.825**	**0.845**	**0.858**	**0.814**
GalagoSenegalensis	53	0.548	0.515	0.635	0.422	0.431	0.412	0.666	0.470
Galagoides demidoff	62	0.685	**0.722**	**0.711**	**0.778**	0.532	0.630	**0.811**	**0.705**
Genetta genetta	32	0.518	0.285	0.607	0.215	0.486	0.466	0.548	0.262
Genetta maculata	104	0.655	0.583	0.686	0.638	0.572	0.630	0.666	0.573
Genetta thierryi	30	**0.738**	**0.854**	**0.898**	**0.762**	**0.942**	**0.898**	**0.953**	**0.919**
Gerbilliscus guineae	27	**0.871**	**0.888**	**0.752**	**0.752**	**0.888**	**0.930**	**0.920**	**0.888**
Gerbilliscus kempi	59	0.596	**0.832**	0.664	**0.793**	**0.708**	**0.726**	0.684	**0.799**
Giraffa camelopardalis	50	0.594	0.526	0.693	**0.720**	0.410	0.387	**0.739**	0.672
Graphiurus kelleni	24	0.587	**0.744**	**0.773**	**0.841**	0.000	0.000	**0.768**	**0.824**
Graphiurus lorraineus	45	**0.734**	**0.735**	**0.776**	**0.791**	**0.785**	**0.836**	**0.788**	**0.751**
Graphiurus nagtglasii	30	**0.786**	**0.869**	**0.786**	**0.942**	**0.785**	**0.789**	**0.787**	**0.953**

TABLE B.8 - ***Continued.***

W.S. Savanna		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Heliosciurus gambianus	99	0.582	0.479	0.535	0.591	0.610	0.605	0.570	0.531
Heliosciurus rufobrachium	213	**0.761**	**0.769**	**0.766**	**0.791**	**0.722**	**0.776**	**0.784**	**0.766**
Herpestes ichneumon	31	0.522	0.692	0.638	**0.704**	0.344	0.410	0.466	**0.773**
Herpestes sanguineus	89	0.370	0.394	0.529	0.445	0.315	0.388	0.536	0.427
Hystrix cristata	42	0.514	0.457	0.490	0.582	0.606	0.563	0.349	0.578
Ichneumia albicauda	32	0.501	0.580	0.352	0.589	0.501	0.266	0.424	0.578
Ictonyx striatus	25	**0.731**	**0.756**	**0.780**	**0.897**	0.000	0.585	**0.723**	**0.863**
Lemniscomys bellieri	15	**0.898**	**0.940**	**0.891**	**0.952**	**0.791**	**0.865**	**0.952**	**0.952**
Lemniscomys striatus	413	**0.754**	0.692	**0.722**	0.693	0.696	0.680	**0.756**	**0.707**
Lemniscomys zebra	60	**0.727**	0.685	**0.721**	**0.807**	**0.763**	0.656	**0.778**	**0.781**
Mastomys erythroleucus	34	**0.945**	**0.810**	**0.919**	**0.810**	**0.925**	0.000	**0.953**	**0.810**
Mastomys natalensis	691	0.543	0.515	0.531	0.514	0.614	0.535	0.537	0.547
Mus haussa	15	**0.927**	**0.780**	**0.908**	**0.902**	**0.842**	0.618	**0.952**	**0.878**
Mus musculoides	371	0.661	0.660	0.599	0.653	0.000	0.645	0.610	0.657
Mus setulosus	86	**0.797**	**0.867**	**0.839**	**0.885**	**0.731**	0.678	**0.883**	**0.880**
Nandinia binotata	44	**0.763**	0.523	**0.873**	0.617	0.608	0.000	**0.825**	0.644
Orycteropus afer	44	0.669	0.582	0.534	0.609	0.523	0.667	0.621	0.589
Panthera leo	79	0.586	0.696	0.628	**0.776**	0.409	0.412	0.636	**0.813**
Papio anubis	44	0.542	**0.810**	**0.783**	**0.820**	0.000	0.000	0.695	**0.818**
Papio papio	39	**0.853**	**0.894**	**0.938**	**0.828**	**0.716**	**0.836**	**0.933**	**0.916**
Phacochoerus africanus	48	0.457	0.603	0.598	0.552	0.477	0.539	0.571	0.628
Phataginus tricuspis	33	**0.806**	**0.886**	**0.848**	**0.908**	0.453	0.000	**0.924**	**0.953**

TABLE B.8 - ***Continued.***

W.S. Savanna		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Praomys daltoni	72	**0.739**	**0.806**	**0.775**	**0.748**	0.655	**0.730**	**0.704**	**0.806**
Praomys derooi	34	**0.758**	**0.926**	**0.894**	**0.920**	**0.818**	**0.765**	**0.852**	**0.953**
Praomys tullbergi	90	0.663	0.671	**0.701**	**0.754**	0.675	0.611	**0.736**	**0.714**
Procavia capensis	126	**0.804**	**0.721**	**0.775**	0.688	**0.712**	**0.728**	**0.781**	0.688
Redunca redunca	24	0.448	0.535	0.676	0.666	**0.732**	**0.738**	**0.752**	0.683
Steatomys caurinus	19	**0.788**	**0.918**	0.450	**0.952**	0.581	**0.785**	**0.806**	**0.947**
Sylvicapra grimmia	92	0.685	**0.761**	**0.747**	0.658	0.481	0.614	**0.738**	0.582
Taterillus gracilis	90	**0.844**	**0.789**	**0.890**	0.679	**0.722**	**0.767**	**0.834**	**0.777**
Thryonomys swinderianus	90	0.639	**0.772**	0.653	**0.856**	0.527	**0.832**	**0.752**	**0.834**
Tragelaphus scriptus	99	**0.740**	0.565	**0.736**	0.610	0.664	0.580	**0.724**	0.564
Uranomys ruddi	59	0.690	**0.847**	0.607	**0.859**	0.613	0.690	**0.754**	**0.927**
Vulpes pallida	26	**0.953**	**0.952**	**0.754**	**0.953**	**0.752**	**0.987**	**0.952**	**0.953**
Xerus erythropus	96	0.602	**0.719**	**0.808**	**0.802**	0.667	**0.852**	**0.842**	**0.906**
REPTILIA									
Afronatrix anoscopus	18	0.234	**0.814**	**0.702**	**0.926**	**0.803**	**0.952**	**0.712**	**0.952**
Afrotyphlops punctatus	15	0.680	0.000	**0.910**	0.455	0.617	0.231	**0.744**	**0.936**
Agama agama	211	0.619	**0.722**	0.675	0.693	0.677	0.694	**0.701**	**0.762**
Agama boueti	27	**0.776**	**0.956**	**0.752**	**0.953**	**0.961**	**0.968**	**0.954**	**0.953**
Agama boulengeri	141	**0.945**	**0.953**	**0.927**	**0.893**	**0.964**	**0.981**	**0.950**	**0.964**
Bitis arietans	286	0.670	**0.728**	0.683	**0.781**	0.000	**0.733**	0.699	**0.744**
Boaedon fuliginosus	139	0.698	0.535	**0.757**	0.590	0.591	0.444	**0.767**	0.588
Boaedon lineatus	17	0.559	**0.925**	0.284	**0.916**	0.285	**0.963**	0.578	**0.952**

TABLE B.8 - ***Continued.***

W.S. Savanna		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Causus maculatus	36	0.590	**0.737**	0.470	**0.770**	0.490	**0.764**	0.639	**0.857**
Causus rhombeatus	162	**0.721**	**0.769**	**0.731**	**0.788**	0.680	**0.716**	**0.756**	**0.794**
Chamaeleo africanus	20	0.662	**0.808**	**0.701**	0.598	0.666	**0.874**	**0.907**	**0.894**
Chamaeleo gracilis	52	**0.789**	0.700	**0.797**	0.666	**0.715**	0.528	**0.748**	**0.707**
Chamaeleo senegalensis	34	**0.728**	0.563	0.569	**0.744**	0.630	0.617	0.646	0.683
Crocodylus sp.	98	0.659	0.645	**0.718**	**0.806**	0.543	0.607	**0.728**	0.686
Crotaphopeltis hotamboeia	233	0.672	**0.711**	**0.701**	**0.740**	**0.750**	**0.739**	0.695	**0.721**
Dasypeltis fasciata	16	**0.824**	**0.933**	0.531	**0.951**	0.588	**0.908**	**0.751**	**0.853**
Dispholidus typus	223	**0.765**	0.699	**0.774**	0.700	**0.771**	0.606	**0.800**	**0.760**
Echis leucogaster	19	0.450	**0.940**	0.687	**0.954**	0.456	**0.976**	**0.843**	**0.952**
Echis ocellatus	20	**0.890**	**0.905**	**0.953**	**0.952**	0.452	**0.957**	**0.912**	**0.952**
Gerrhosaurus major	31	**0.769**	0.626	**0.786**	**0.902**	**0.822**	**0.786**	**0.777**	**0.885**
Grayia smythii	20	0.538	**0.823**	0.385	**0.701**	0.614	0.594	0.516	0.661
Hemidactylus angulatus	58	**0.766**	**0.786**	**0.785**	**0.733**	0.690	**0.788**	**0.890**	**0.839**
Hemidactylus brookii	52	0.624	0.563	0.553	**0.833**	**0.730**	0.683	0.612	**0.748**
Hemidactylus fasciatus	33	**0.948**	**0.953**	**0.795**	**0.923**	0.671	**0.962**	**0.953**	**0.953**
Hemidactylus mabouia	288	**0.712**	0.675	**0.709**	**0.770**	0.647	0.643	**0.708**	**0.701**
Hemidactylus muriceus	18	**0.952**	**0.701**	**0.885**	**0.952**	**0.909**	**0.740**	**0.717**	**0.922**
Kinixys belliana	32	0.431	0.589	**0.775**	**0.734**	0.170	0.496	0.690	0.473
Lygodactylus gutturalis	23	**0.952**	0.551	**0.953**	**0.918**	**0.913**	0.553	**0.952**	**0.848**
Meizodon coronatus	15	**0.913**	0.593	0.618	**0.865**	**0.894**	0.000	**0.780**	**0.735**
Naja melanoleuca	83	**0.790**	0.683	**0.812**	0.694	0.682	0.563	**0.802**	0.687

TABLE B.8 - ***Continued.***

W.S. Savanna		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Naja nigricollis	79	0.400	0.328	0.625	0.399	0.393	0.393	0.530	0.457
Pelomedusa subrufa	117	0.535	0.684	0.581	0.637	0.471	0.626	0.645	0.678
Philothamnus irregularis	45	0.663	0.666	**0.927**	0.655	0.000	**0.702**	**0.889**	0.644
Philothamnus semivariegatus	163	**0.747**	**0.737**	**0.706**	**0.714**	0.584	0.680	**0.713**	**0.748**
Psammophis elegans	21	**0.848**	**0.817**	**0.944**	**0.931**	0.450	0.450	**0.894**	**0.822**
Psammophis lineatus	19	0.437	0.000	0.549	**0.948**	0.454	0.658	0.638	**0.764**
Psammophis phillipsi	75	0.483	0.505	**0.701**	**0.780**	0.589	**0.705**	**0.711**	**0.771**
Psammophis sibilans	64	0.554	0.335	0.651	0.530	0.476	0.427	0.563	0.320
Ptyodactylus ragazzi	31	**0.818**	**0.740**	**0.773**	**0.761**	**0.876**	**0.804**	**0.840**	**0.902**
Python sebae	48	0.407	0.442	0.458	0.478	0.259	0.422	0.610	0.342
Rhamphiophis oxyrhynchus	19	**0.809**	0.408	**0.768**	**0.714**	0.632	0.606	**0.780**	**0.824**
Scaphiophis albopunctatus	21	**0.713**	0.511	**0.842**	0.570	0.518	0.683	**0.890**	0.534
Tarentola annularis	24	0.538	**0.808**	**0.752**	0.634	**0.812**	0.000	**0.873**	0.676
Tarentola ephippiata	29	0.619	**0.953**	0.612	**0.925**	0.452	0.000	0.619	**0.953**
Tarentola parvicarinata	130	**0.931**	**0.962**	**0.933**	**0.924**	**0.963**	**0.972**	**0.964**	**0.963**
Toxicodryas blandingii	32	**0.839**	0.579	**0.742**	0.657	**0.832**	0.535	**0.764**	**0.705**
Trachylepis affinis	50	**0.763**	**0.781**	**0.828**	**0.753**	0.607	0.690	**0.826**	**0.893**
Trachylepis albilabris	18	**0.718**	0.490	**0.702**	**0.702**	**0.703**	0.471	**0.874**	**0.708**
Trachylepis quinquetaeniata	168	0.519	0.643	0.624	0.675	0.467	0.567	**0.701**	**0.731**
Tropiocolotes tripolitanus	32	**0.942**	**0.953**	**0.785**	**0.953**	**0.969**	**0.963**	**0.941**	**0.954**
Uromastyx dispar	24	**0.992**	**0.984**	**0.970**	**0.982**	**0.998**	**0.998**	**0.990**	**0.980**
Varanus exanthematicus	32	0.476	0.358	0.611	0.464	0.432	0.117	0.654	0.428

TABLE B.8 - ***Continued.***

W.S. Savanna		GLM		GBM		ANN		MaxEnt	
Taxa	N	PA1	PA2	PA1	PA2	PA1	PA2	PA1	PA2
Varanus niloticus	179	0.663	**0.752**	0.660	0.655	0.402	0.627	**0.712**	**0.731**

TABLE B.9 - ***Regression (R2) scores between species richness of functional groups and bio-indicators. fAPAR, rainfall, RUE, SM and SMUE are coded according to the aggregations of different productivity periods. The different productivity periods correspond to the cyclic fraction (cyfr), dry season (dry) and vegetation year (veg). All bio-indicators were temporally aggregated between 2002-2012 based on the mean (M) and variation (V) statistics. The most significant R2 scores (>0.25) are highlighted in bold.***

	fAPAR cyfr		fAPAR dry		fAPAR veg		Rain cyfr		Rain veg		RUE cyfr		RUE dry		RUE veg		SM cyfr		SM veg		SMUE cyfr		SMUE dry		SMUE veg		L veg
	M	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**
Australian																											
Ecto_SmBS	0.05	0.11	0.16	0.14	0.13	0.13	**0.44**	0.21	**0.40**	0.16	**0.26**	0.11	0.12	0.11	0.09	0.06	**0.40**	**0.34**	**0.36**	**0.29**	0.10	0.10	0.19	0.12	0.17	0.08	0.09
MeFEC	0.05	0.08	0.11	0.09	0.14	0.07	0.04	0.08	0.06	0.12	0.03	0.05	0.14	0.11	0.18	0.07	0.21	0.18	0.25	0.14	0.02	0.06	0.05	0.09	0.05	0.07	0.03
Ecto_MeEOO	0.03	0.00	0.03	0.02	0.04	0.02	0.04	0.04	0.05	0.05	0.01	0.00	0.02	0.01	0.03	0.02	0.06	0.02	0.07	0.02	0.01	0.00	0.03	0.02	0.03	0.02	0.01
SmBS	0.00	0.02	0.03	0.01	0.03	0.02	0.12	0.07	0.14	0.06	0.03	0.02	0.03	0.00	0.01	0.01	0.05	0.05	0.04	0.05	0.02	0.02	0.04	0.01	0.04	0.02	0.02
Ecto_MeFEC	0.10	0.09	0.06	0.09	0.04	0.06	0.22	0.10	0.19	0.16	**0.32**	0.10	0.09	0.09	0.14	0.01	**0.55**	**0.32**	**0.52**	0.24	0.07	0.08	0.05	0.07	0.03	0.02	0.03
Ecto_SmEOO	0.03	0.03	0.24	0.18	0.23	0.20	**0.32**	0.17	**0.31**	0.05	0.08	0.00	0.17	0.15	0.12	0.18	0.06	0.10	0.05	0.04	0.05	0.04	0.22	0.20	0.22	0.21	0.16
LgBS	0.08	0.04	0.15	0.12	0.19	0.07	0.15	0.04	0.17	0.06	0.05	0.02	0.16	0.11	0.21	0.05	0.10	0.07	0.13	0.05	0.02	0.03	0.08	0.11	0.09	0.06	0.04
Water	0.02	0.02	0.16	0.12	0.17	0.11	**0.26**	0.15	**0.27**	0.06	0.05	0.00	0.11	0.09	0.09	0.10	0.07	0.08	0.06	0.04	0.03	0.03	0.15	0.13	0.16	0.11	0.10
Total	0.05	0.02	0.17	0.10	0.19	0.09	0.18	0.10	0.22	0.06	0.03	0.00	0.15	0.10	0.14	0.09	0.10	0.07	0.10	0.04	0.01	0.02	0.13	0.11	0.13	0.10	0.07
Caatinga																											
Endo_MeFEC	0.00	0.00	0.02	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.01
SmBS	0.02	0.02	0.13	0.08	0.05	0.01	0.07	0.05	0.07	0.06	0.04	0.06	0.23	0.06	0.19	0.02	0.02	0.04	0.05	0.09	0.03	0.03	0.07	0.05	0.01	0.01	0.09
Endo_MeBS	0.01	0.01	0.12	0.00	0.05	0.05	0.08	0.01	0.08	0.01	0.04	0.04	0.06	0.01	0.01	0.01	0.04	NA	0.04	0.01	0.01	0.02	0.09	0.00	0.11	0.03	0.02
Water_SmEOO	0.07	0.01	0.17	0.00	0.05	0.07	0.08	0.08	0.08	0.08	0.09	0.07	0.18	0.00	0.09	0.00	0.06	0.07	0.11	0.13	0.10	0.04	0.07	0.01	0.01	0.02	0.07
Endo_LoFEC	0.01	0.03	0.02	0.05	0.01	0.01	0.07	0.01	0.07	0.02	0.02	0.02	0.05	0.06	0.04	0.01	0.00	0.01	0.00	0.02	0.01	0.03	0.01	0.05	0.00	0.01	0.00
Ecto_MeBS	0.01	0.01	0.03	0.00	0.02	0.04	0.06	0.01	0.06	0.01	0.01	0.00	0.02	0.01	0.02	0.00	0.06	0.03	0.06	0.04	0.02	0.00	0.01	0.01	0.01	0.01	0.03
Water_LgEOO	0.00	0.01	0.11	0.01	0.10	0.02	0.07	0.02	0.08	0.02	0.00	0.03	0.07	0.02	0.05	0.02	0.05	0.04	0.06	0.07	0.01	0.01	0.05	0.01	0.02	0.01	0.03
Ecto_LgEOO	0.00	0.02	0.08	0.04	0.06	0.01	0.09	0.03	0.08	0.03	0.01	0.05	0.13	0.07	0.14	0.06	0.07	0.06	0.09	0.11	0.01	0.02	0.03	0.05	0.01	0.01	0.06
Water_MeEOO	0.02	0.00	0.16	0.02	0.09	0.10	0.07	0.05	0.07	0.05	0.01	0.05	0.19	0.07	0.10	0.04	0.02	0.08	0.03	0.11	0.03	0.01	0.08	0.05	0.04	0.04	0.08
Total	0.02	0.03	0.22	0.08	0.07	0.01	0.06	0.03	0.06	0.03	0.05	0.09	**0.30**	0.10	0.22	0.02	0.02	0.07	0.07	0.13	0.04	0.05	0.11	0.05	0.02	0.02	0.11

TABLE B.9 - ***Continued.***

	fAPAR cyfr		fAPAR dry		fAPAR veg		Rain cyfr		Rain veg		RUE cyfr		RUE dry		RUE veg		SM cyfr		SM veg		SMUE cyfr		SMUE dry		SMUE veg		L veg
	M	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**
SW-Africa																											
SmBS	0.04	0.06	0.23	**0.25**	0.04	**0.27**	0.20	**0.41**	0.21	**0.40**	0.19	0.03	0.19	0.24	0.02	0.23	**0.31**	**0.26**	**0.35**	0.18	0.03	0.04	0.17	0.24	0.06	**0.25**	0.11
Ecto_SmBS	0.07	0.04	0.07	0.09	0.07	0.04	0.18	0.06	0.18	0.06	0.04	0.02	0.05	0.09	0.03	0.03	0.03	0.06	0.02	0.09	0.06	0.02	0.06	0.09	0.06	0.04	0.02
Ecto_MeEOO	0.03	0.03	0.08	0.11	0.03	0.07	0.08	0.09	0.09	0.08	0.04	0.01	0.07	0.10	0.02	0.06	0.11	0.05	0.11	0.03	0.02	0.02	0.07	0.10	0.02	0.08	0.02
Ecto_MeBS	0.04	0.01	0.01	0.02	0.04	0.02	0.03	0.05	0.04	0.05	0.07	0.00	0.01	0.02	0.02	0.03	0.07	0.01	0.07	0.03	0.07	0.02	0.01	0.02	0.02	0.03	0.00
Ecto_MeFEC	0.06	0.04	0.15	0.17	0.06	0.21	0.11	**0.45**	0.13	**0.46**	0.24	0.02	0.13	0.19	0.02	0.21	**0.26**	**0.25**	**0.30**	0.19	0.08	0.03	0.11	0.16	0.03	0.18	0.11
Ecto_LgBS	0.07	0.05	0.15	0.18	0.07	0.22	0.11	**0.45**	0.12	**0.45**	0.23	0.02	0.13	0.20	0.02	0.22	**0.26**	0.24	**0.30**	0.18	0.09	0.04	0.11	0.17	0.04	0.18	0.10
Endo_LoFEC	0.07	0.04	0.16	0.19	0.07	0.22	0.12	**0.46**	0.13	**0.46**	0.23	0.02	0.13	0.21	0.02	0.23	**0.26**	**0.25**	**0.29**	0.16	0.08	0.03	0.12	0.17	0.04	0.19	0.10
Water	0.08	0.04	0.15	0.17	0.08	0.20	0.10	**0.46**	0.12	**0.47**	0.24	0.02	0.13	0.19	0.02	0.20	**0.26**	**0.25**	**0.29**	0.20	0.10	0.03	0.11	0.16	0.03	0.18	0.10
Endo_SmBS	0.08	0.03	0.14	0.16	0.08	0.19	0.10	**0.43**	0.12	**0.44**	0.24	0.02	0.12	0.18	0.02	0.20	**0.25**	0.24	**0.29**	0.18	0.10	0.03	0.10	0.15	0.03	0.17	0.09
Endo_MeFEC	0.06	0.04	0.15	0.18	0.06	0.21	0.12	**0.45**	0.13	**0.45**	0.24	0.02	0.13	0.20	0.02	0.21	**0.26**	0.24	**0.29**	0.19	0.08	0.03	0.11	0.16	0.04	0.18	0.10
Total	0.02	0.01	0.04	0.05	0.02	0.02	0.11	0.02	0.10	0.02	0.02	0.01	0.02	0.05	0.00	0.01	0.03	0.03	0.03	0.04	0.03	0.01	0.03	0.05	0.02	0.03	0.02
S-Europe																											
Endo_SmBS	0.00	0.08	0.05	0.01	0.05	0.11	0.18	0.14	0.22	0.19	0.02	0.11	0.02	0.04	0.02	0.14	0.09	0.05	0.14	0.07	0.01	0.07	0.03	0.01	0.03	0.06	0.01
Endo_LgEOO	0.05	0.16	0.06	0.00	0.14	0.10	**0.31**	0.14	**0.37**	0.17	0.01	0.18	0.02	0.01	0.00	0.08	0.19	0.11	0.25	0.13	0.02	0.14	0.02	0.00	0.03	0.06	0.01
Endo_LgBS	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.03	0.01	0.03	0.03	0.01	0.04	0.01	0.01	0.00	0.01	0.02	0.01	0.01	0.00
Water_MeFEC	0.05	0.14	0.16	0.07	0.25	0.13	**0.39**	0.05	**0.41**	0.03	0.00	0.13	0.06	0.04	0.05	0.06	0.12	0.06	0.16	0.07	0.03	0.13	0.11	0.07	0.16	0.11	0.03
Water_HiFEC	0.03	0.01	0.01	0.02	0.06	0.01	0.14	0.01	0.14	0.02	0.01	0.01	0.01	0.02	0.04	0.01	0.02	0.06	0.02	0.10	0.04	0.01	0.02	0.03	0.06	0.01	0.02
MeBS	0.01	0.13	0.04	0.01	0.06	0.10	**0.27**	0.15	**0.33**	0.17	0.01	0.14	0.02	0.02	0.02	0.09	0.20	0.13	**0.26**	0.15	0.00	0.10	0.01	0.00	0.01	0.06	0.00
Ecto_SmBS	0.00	0.08	0.04	0.00	0.06	0.10	**0.26**	0.15	**0.30**	0.23	0.02	0.11	0.01	0.01	0.02	0.06	0.12	0.12	0.19	0.22	0.01	0.06	0.01	0.00	0.01	0.02	0.03
Endo_MeFEC	0.00	0.04	0.01	0.01	0.02	0.05	0.07	0.10	0.08	0.13	0.01	0.07	0.01	0.05	0.01	0.12	0.06	0.02	0.10	0.02	0.00	0.04	0.01	0.01	0.01	0.02	0.00
Ecto_MeFEC	0.05	0.03	0.00	0.00	0.04	0.00	0.05	0.02	0.05	0.04	0.03	0.02	0.00	0.01	0.01	0.01	0.03	0.02	0.05	0.03	0.05	0.03	0.00	0.00	0.03	0.00	0.05
Total	0.02	0.03	0.02	0.02	0.04	0.03	0.09	0.02	0.08	0.02	0.00	0.04	0.02	0.03	0.03	0.05	0.03	0.01	0.04	0.02	0.01	0.03	0.02	0.02	0.03	0.03	0.01

TABLE B.9 - ***Continued.***

	fAPAR cyfr		fAPAR dry		fAPAR veg		Rain cyfr		Rain veg		RUE cyfr		RUE dry		RUE veg		SM cyfr		SM veg		SMUE cyfr		SMUE dry		SMUE veg		L veg
	M	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**	**V**	**M**
WS-Savannah																											
Endo_SmBS	**0.27**	0.14	**0.25**	0.15	**0.31**	0.19	**0.40**	0.24	**0.40**	0.24	0.05	0.12	0.15	0.18	0.12	0.19	**0.31**	0.13	**0.34**	0.13	0.10	0.13	0.16	0.13	0.13	0.14	**0.29**
Water	0.08	0.02	0.08	0.02	0.14	0.04	0.18	0.00	0.18	0.00	0.01	0.02	0.04	0.01	0.03	0.02	0.07	0.00	0.13	0.02	0.03	0.02	0.04	0.02	0.05	0.03	0.11
Endo_MeBS	**0.30**	0.21	**0.29**	0.24	**0.33**	0.23	**0.36**	0.04	**0.36**	0.04	0.19	0.19	**0.26**	0.24	0.24	0.22	0.13	0.03	0.21	0.01	**0.27**	0.21	**0.29**	0.25	**0.28**	0.24	**0.30**
Ecto_LgBS	0.06	0.03	0.06	0.03	0.08	0.03	0.08	0.02	0.08	0.02	0.01	0.03	0.03	0.03	0.03	0.04	0.06	0.01	0.13	0.01	0.04	0.04	0.04	0.03	0.04	0.05	0.06
Endo_LoFEC	0.18	0.11	0.15	0.13	0.18	0.12	0.20	0.01	0.20	0.01	0.09	0.10	0.12	0.13	0.12	0.12	0.07	0.02	0.10	0.01	0.15	0.10	0.16	0.13	0.15	0.11	0.17
Ecto_SmBS	**0.46**	**0.30**	**0.40**	**0.37**	**0.46**	**0.33**	**0.52**	0.08	**0.52**	0.07	**0.25**	**0.26**	**0.34**	**0.36**	**0.33**	**0.31**	0.22	0.05	**0.33**	0.01	**0.38**	**0.29**	**0.40**	**0.37**	**0.40**	**0.32**	**0.42**
Endo_MeFEC	0.20	0.14	0.21	0.15	0.23	0.18	**0.33**	0.14	**0.33**	0.14	0.07	0.12	0.13	0.15	0.11	0.16	**0.25**	0.09	**0.30**	0.07	0.10	0.12	0.15	0.12	0.13	0.13	0.22
Ecto_MeBS	**0.30**	0.13	0.21	0.11	**0.29**	0.16	**0.30**	0.14	**0.30**	0.14	0.06	0.06	0.12	0.11	0.10	0.09	**0.26**	0.10	**0.28**	0.11	0.11	0.10	0.14	0.09	0.13	0.09	0.20
Total	0.14	0.02	0.06	0.04	0.14	0.03	0.13	0.11	0.13	0.12	0.02	0.01	0.02	0.06	0.04	0.03	0.12	0.11	0.11	0.16	0.03	0.02	0.04	0.03	0.04	0.02	0.11

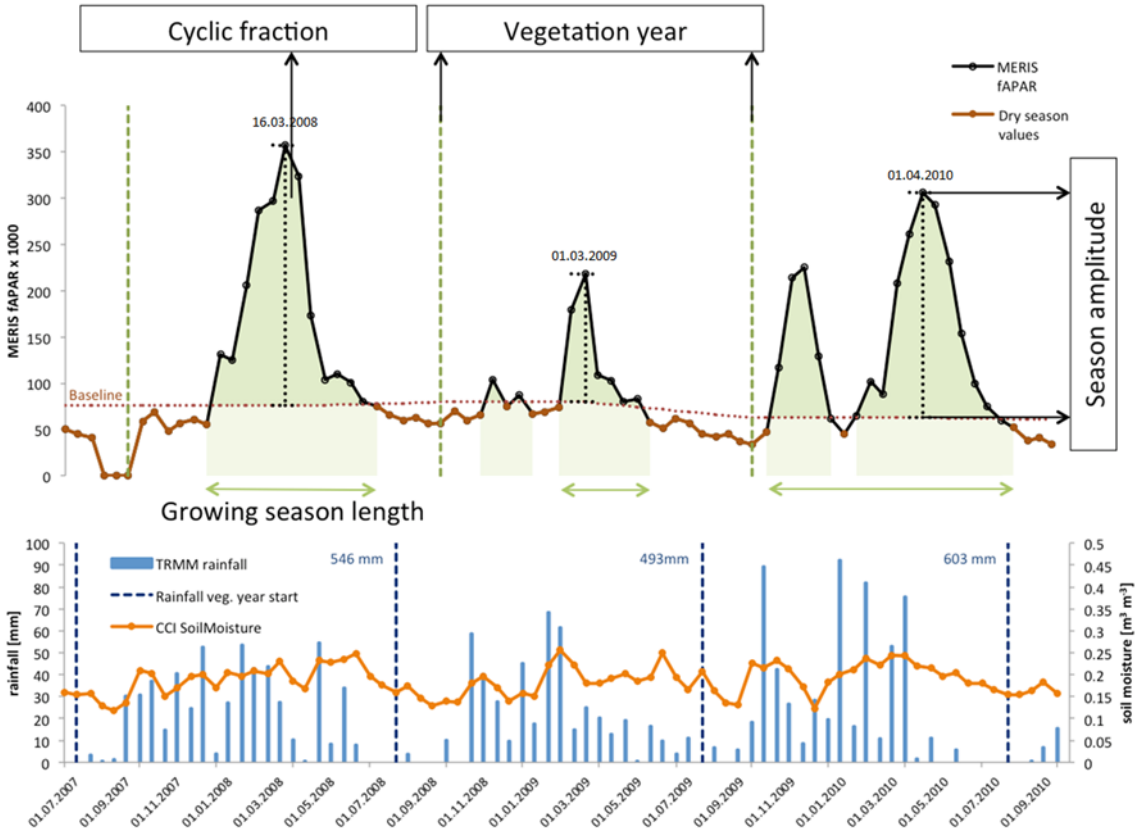

FIG. B.1 - ***Scheme of the extracted phenological descriptors and periods, and corresponding rainfall and soil moisture data.***

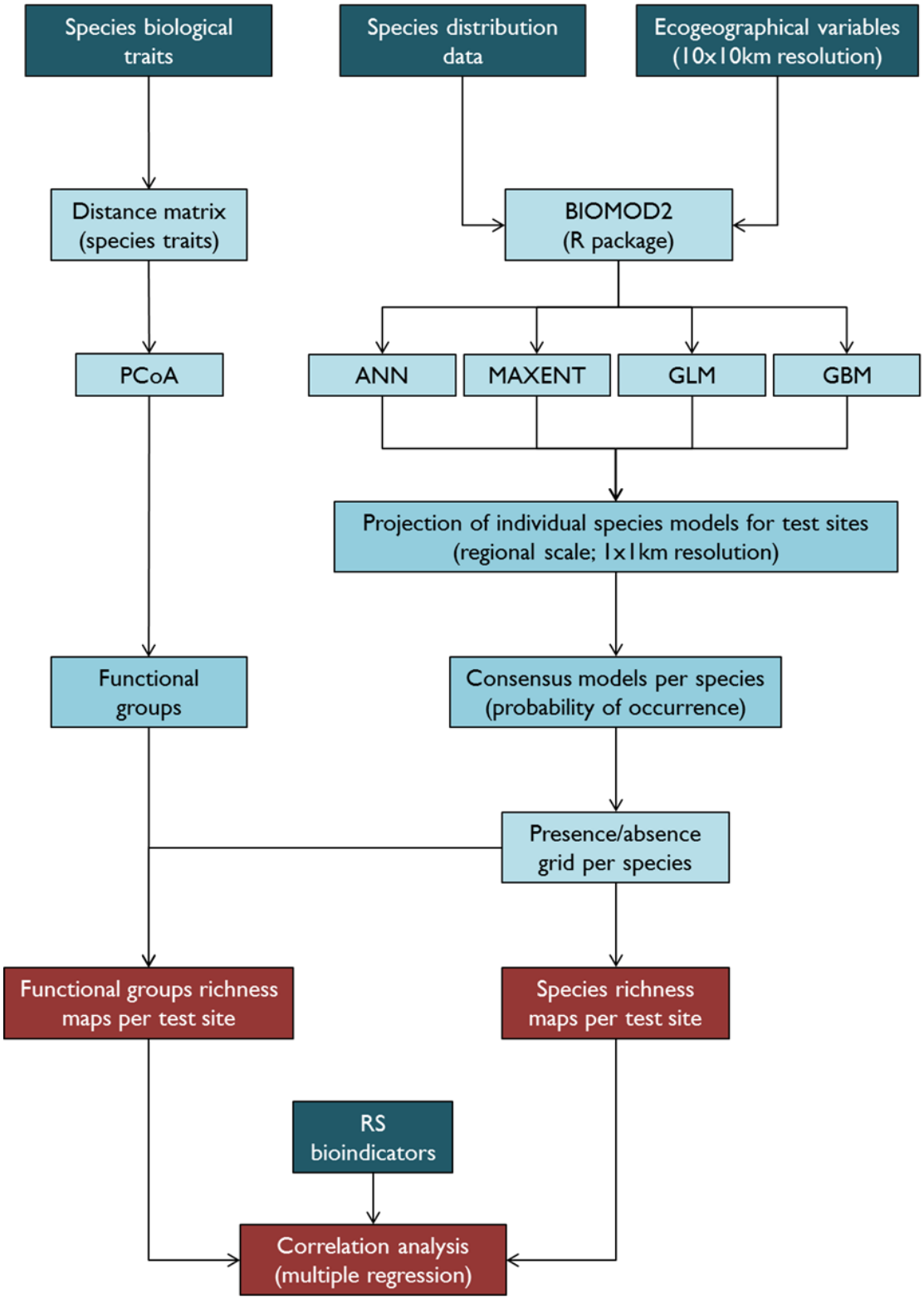

FIG. B.2 - ***Methodological overview. Boxes are representing major inputs (dark blue), methodological steps and intermediate outputs (light blue), and major outputs (red).***

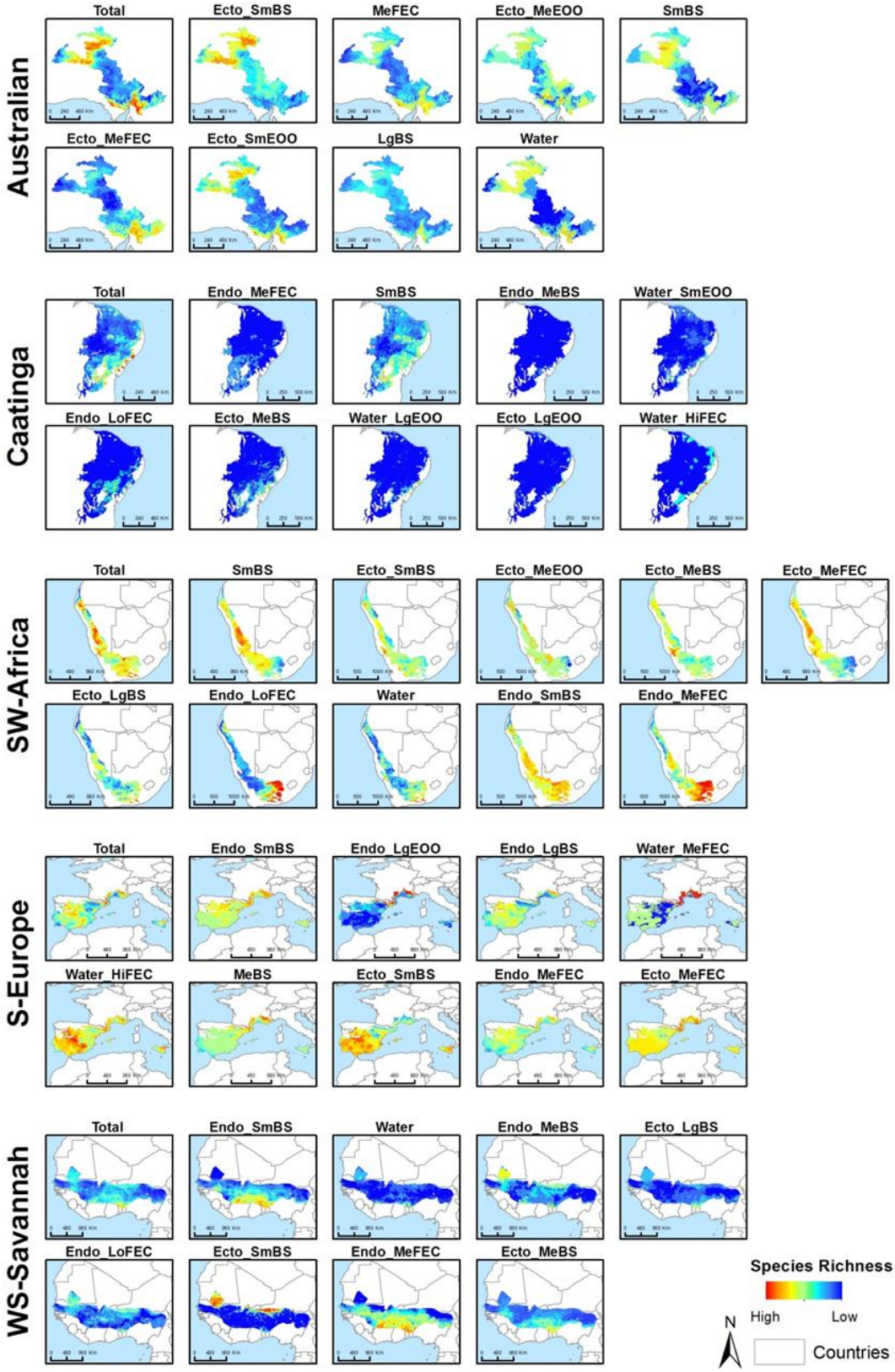

FIG. B.3 - ***Distribution of species richness in each dryland. Maps display richness of total species (Total) and of each functional group identified, derived by ecological modelling. Codes of functional groups are available in Table 4.2.***

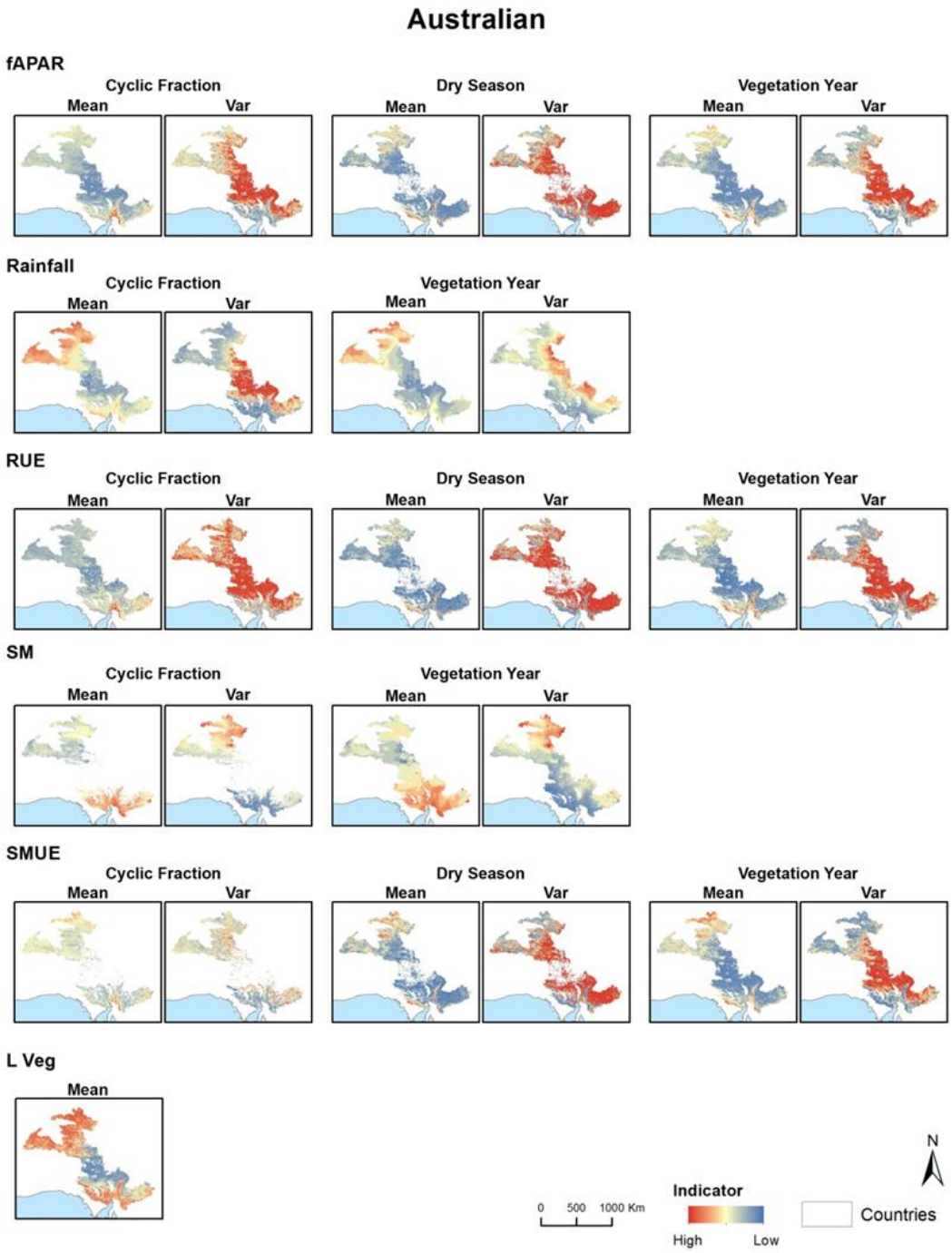

FIG. B.4 - ***Distribution of bio-indicators in each dryland. Codes of bio-indicators are available in Table B.1.***

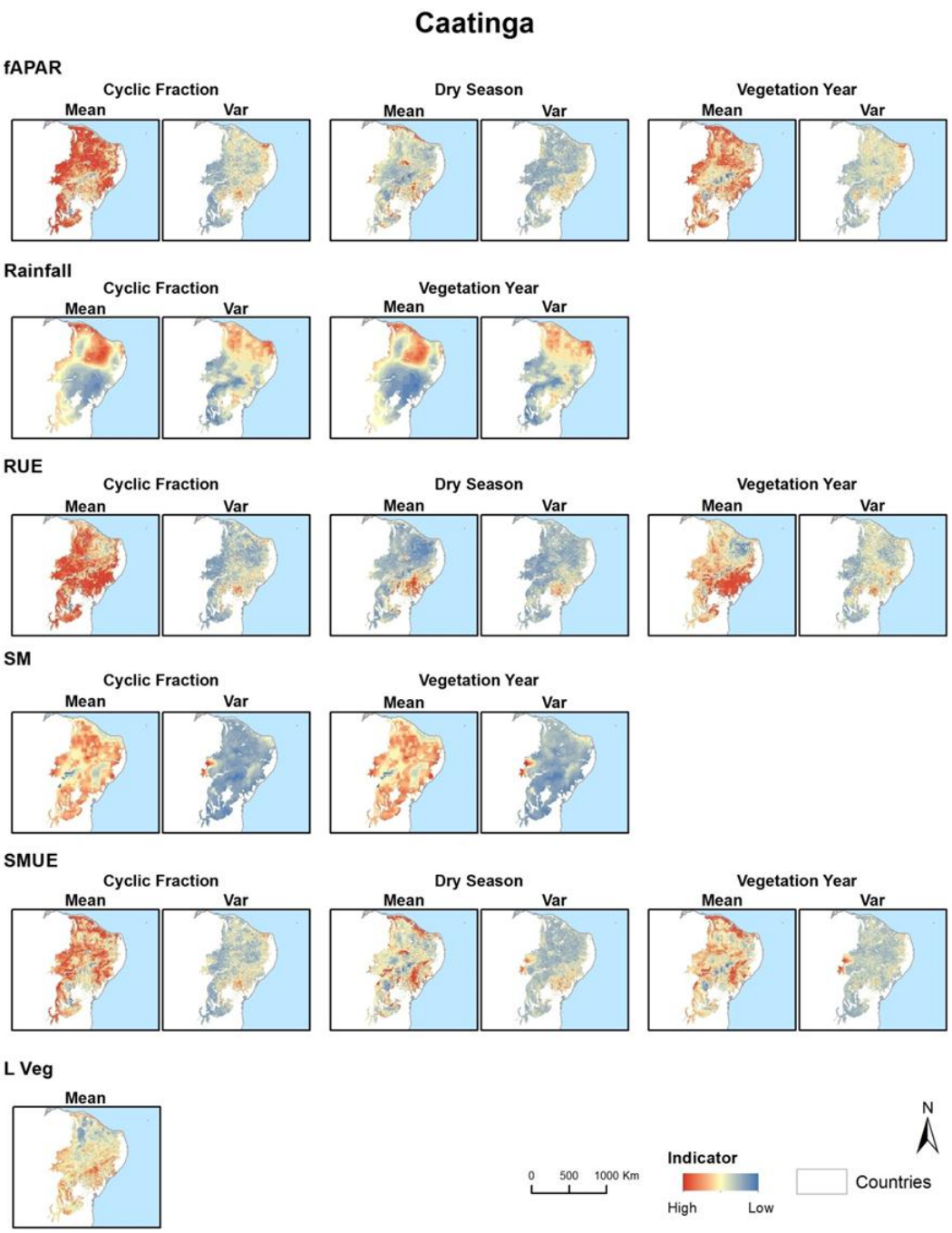

FIG. B.4 - *Continued.*

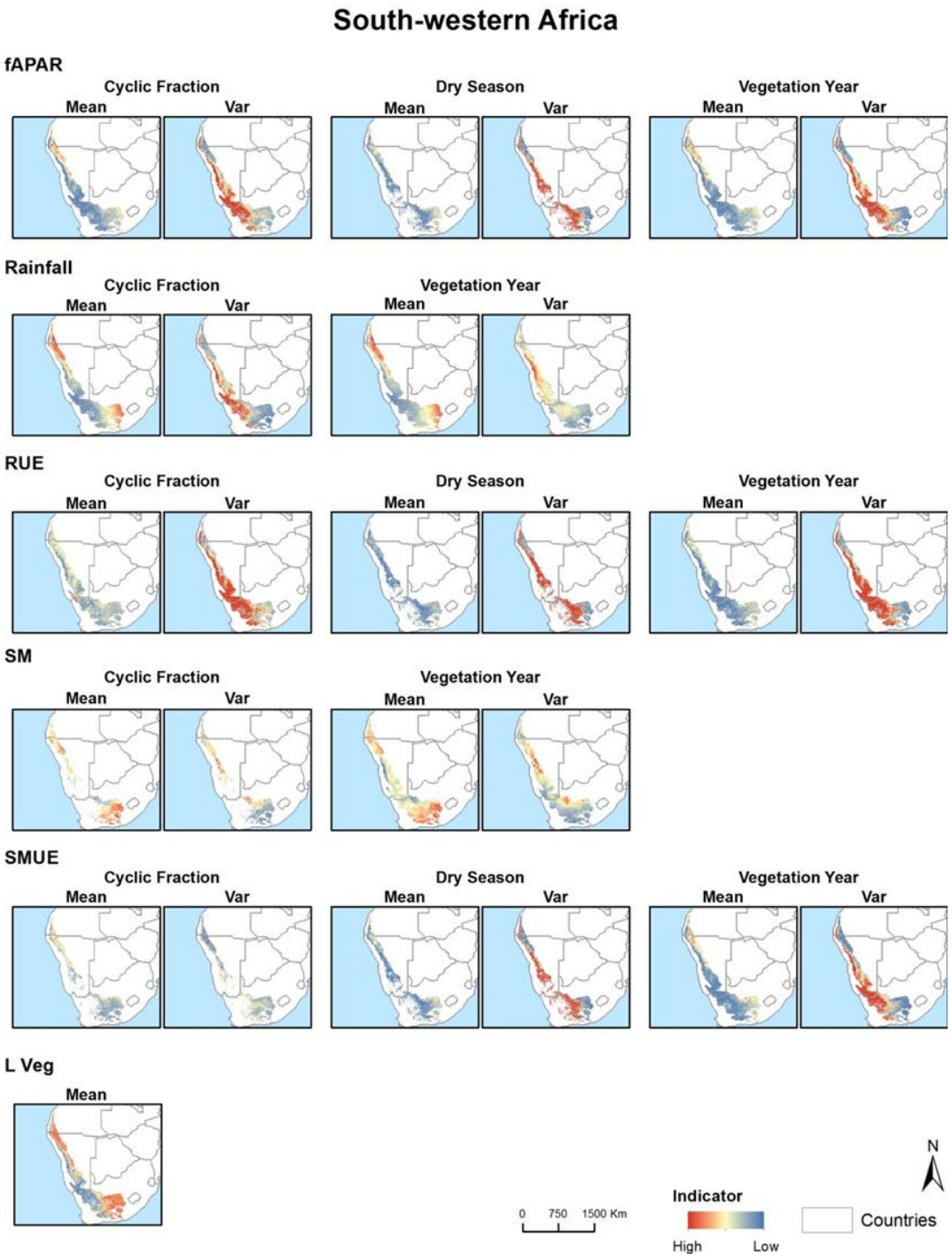

FIG. B.4 - ***Continued.***

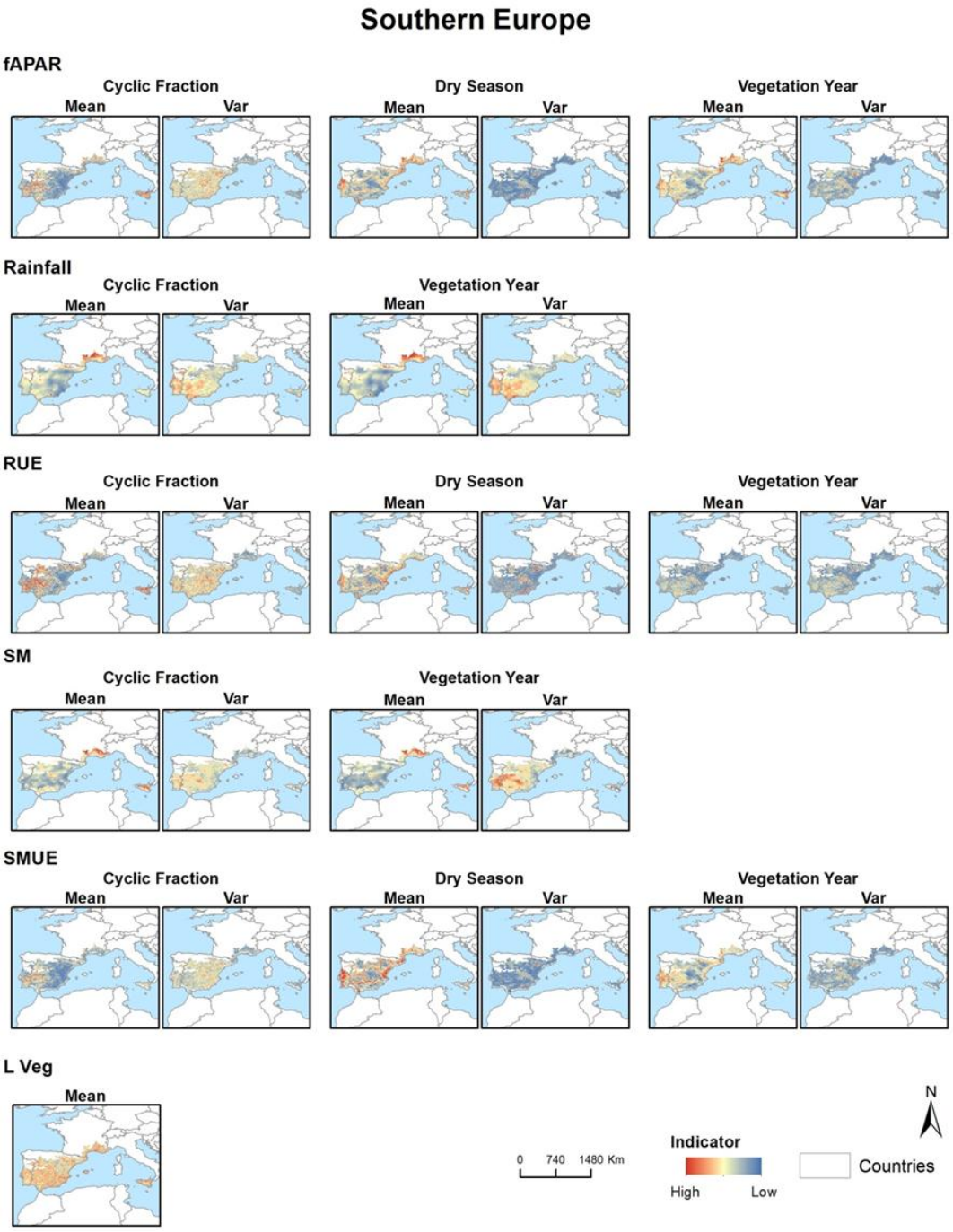

FIG. B.4 - *Continued.*

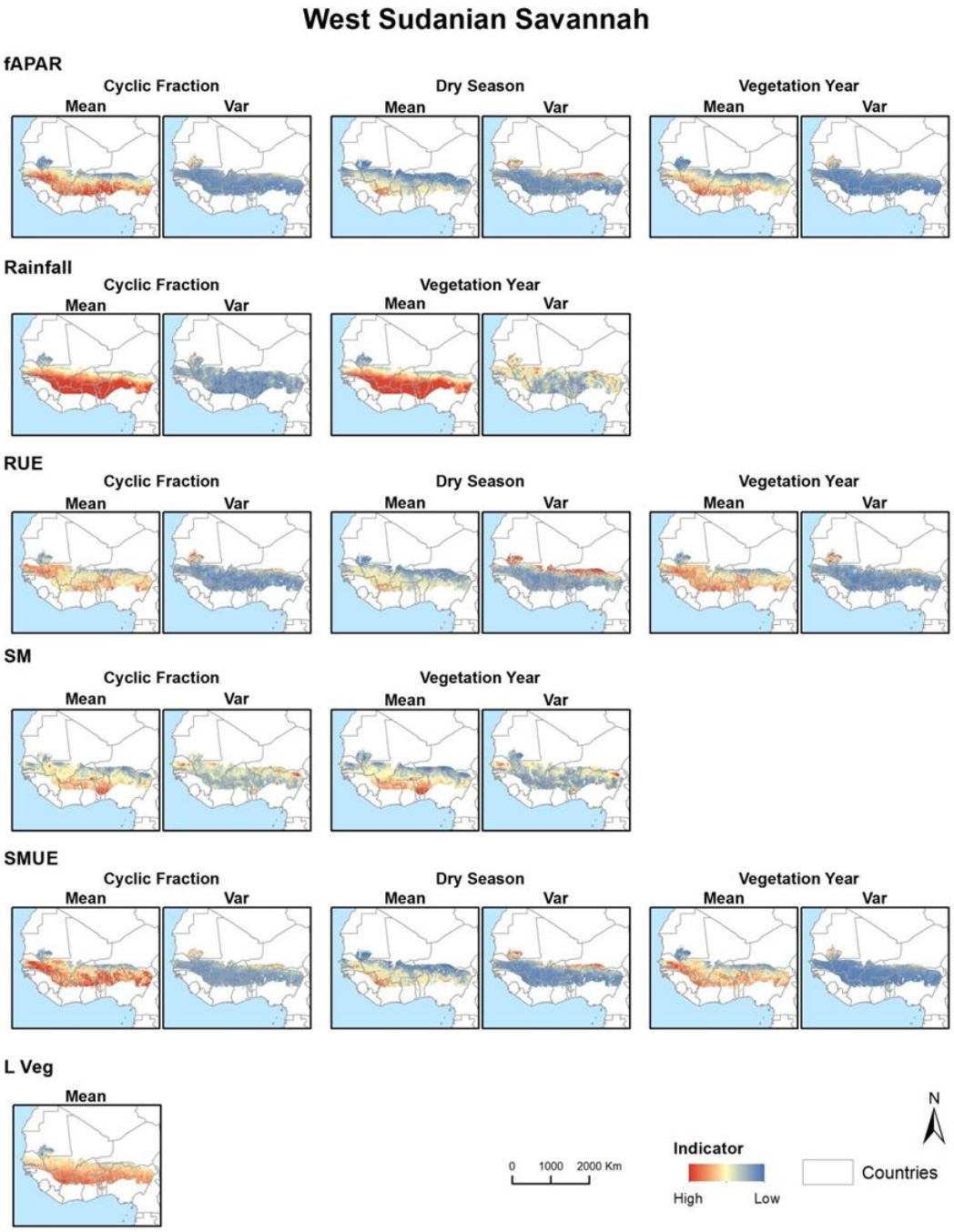

FIG. B.4 - *Continued.*

APPENDIX C

Revealing unknown land cover heterogeneity in the West Sahara-Sahel and its implications for biodiversity conservation

TABLE C.1 - ***Landsat 8 image information used in this work. The path and row of each Landsat scene are indicated as well as the acquisition dates corresponding to the two temporal periods considered in this study.***

Path	Row	Acquisition date 1	Acquisition date 2
197	49	15/12/2014	29/01/2014
197	50	15/12/2014	29/01/2014
198	43	04/11/2014	20/01/2014
198	44	04/11/2014	20/01/2014
198	45	19/10/2014	20/01/2014
198	46	19/10/2014	20/01/2014
198	47	19/10/2014	20/01/2014
198	48	19/10/2014	20/01/2014
198	49	19/10/2014	20/01/2014
198	50	06/12/2014	20/01/2014
199	40	11/11/2014	28/02/2014
199	41	11/11/2014	28/02/2014
199	42	11/11/2014	28/02/2014
199	43	11/11/2014	27/01/2014
199	44	27/11/2014	28/02/2014
199	45	11/11/2014	28/02/2014
199	46	11/11/2014	12/02/2014
199	47	11/11/2014	28/02/2014
199	48	11/11/2014	27/01/2014
199	49	11/11/2014	27/01/2014
199	50	11/11/2014	27/01/2014
200	39	20/12/2014	02/01/2014
200	40	18/11/2014	18/01/2014
200	41	18/11/2014	18/01/2014
200	42	18/11/2014	18/01/2014
200	43	18/11/2014	03/02/2014
200	44	18/11/2014	02/01/2014
200	45	18/11/2014	18/01/2014
200	46	18/11/2014	18/01/2014
200	47	02/11/2014	18/01/2014
200	48	02/11/2014	18/01/2014
200	49	02/11/2014	18/01/2014
200	50	02/11/2014	03/02/2014
201	39	27/12/2014	25/01/2014
201	40	25/11/2014	25/01/2014
201	41	25/11/2014	26/02/2014
201	42	25/11/2014	26/02/2014
201	43	09/11/2014	26/02/2014
201	44	25/11/2014	26/02/2014

TABLE C.1 - ***Continued.***

Path	Row	Acquisition date 1	Acquisition date 2
201	44	25/11/2014	26/02/2014
201	45	25/11/2014	25/01/2014
201	46	25/11/2014	10/02/2014
201	47	25/11/2014	26/02/2014
201	48	11/12/2014	26/02/2014
201	49	27/12/2014	14/03/2014
201	50	27/12/2014	09/01/2014
202	39	15/10/2014	05/03/2014
202	40	18/12/2014	01/02/2014
202	41	16/11/2014	01/02/2014
202	42	16/11/2014	01/02/2014
202	43	16/11/2014	16/01/2014
202	44	16/11/2014	16/01/2014
202	45	16/11/2014	16/01/2014
202	46	16/11/2014	01/02/2014
202	47	16/11/2014	01/02/2014
202	48	31/10/2014	16/01/2014
202	49	31/10/2014	16/01/2014
202	50	31/10/2014	16/01/2014
203	39	22/10/2014	07/01/2014
203	40	22/10/2014	07/01/2014
203	41	07/11/2014	07/01/2014
203	42	07/11/2014	07/01/2014
203	43	07/11/2014	24/02/2014
203	44	07/11/2014	24/02/2014
203	45	07/11/2014	08/02/2014
203	46	07/11/2014	12/03/2014
203	47	07/11/2014	12/03/2014
203	48	07/11/2014	23/01/2014
203	49	07/11/2014	23/01/2014
203	50	07/11/2014	23/01/2014
204	40	14/11/2014	19/03/2014
204	41	14/11/2014	04/04/2014
204	42	14/11/2014	19/03/2014
204	43	14/11/2014	14/01/2014
204	44	16/12/2014	30/01/2014
204	45	16/12/2014	30/01/2014
204	46	16/12/2014	15/02/2014
204	47	16/12/2014	15/02/2014
204	48	13/10/2014	14/01/2014
204	49	13/10/2014	14/01/2014
204	50	14/11/2014	14/01/2014
205	41	23/12/2014	26/03/2014

TABLE C.1 - ***Continued.***

Path	Row	Acquisition date 1	Acquisition date 2
205	42	23/12/2014	05/01/2014
205	43	23/12/2014	05/01/2014
205	44	23/12/2014	06/02/2014
205	45	05/11/2014	21/01/2014
205	46	05/11/2014	21/01/2014
205	47	20/10/2014	21/01/2014
205	48	05/11/2014	21/01/2014
205	49	05/11/2014	05/01/2014
205	50	21/11/2014	21/01/2014
206	43	12/11/2014	12/01/2014
206	44	12/11/2014	12/01/2014
206	45	12/11/2014	12/01/2014
206	46	12/11/2014	30/12/2014
206	47	12/11/2014	12/01/2014

TABLE C.2 - ***Land-cover classes considered for the final land cover map and their correspondent description.***

Land-cover class	Code	Description
Compact soil	COMPSO	Normally found in large floodplains. Soils frequently composed by silt and/or clay and with sparse or no vegetation cover.
Gravel + Sand floodplains	GSFL	Usually found in large floodplains, in transitions between rocky and sandy soils. Soil composed by similar amounts of gravel and sand and with sparse or no vegetation cover.
Yellow dunes	YDUN	Frequently fixed dunes composed by yellow sand. Sparse shrubs with isolated *Acacia sp.* or with no vegetation cover.
Grasslands	GRAS	Flat flooding areas covered by grasses (e.g., *Cenchrus biflorus*) and mostly associated to Sahelian regions.
Gravel floodplains	GRFL	Large floodplains covered by gravel (locally known as *Reg*) and usually with no vegetation cover.
White dunes	WDUN	Mobile dunes composed by white sand (e.g., barchan dunes). No vegetation cover.
Bare rock	ROCK	Large rock outcrops usually associated to mountain regions.
Orange dunes	ODUN	Frequently fixed dunes composed by orange sand. Sparse shrubs with isolated *Acacia sp.* or sometimes with no vegetation cover.
Compact sand	COMPS	Large flat areas composed by consolidated sandy soils. Presence of shrubs and sparse trees (e.g., *Acacia sp.*).
Savannah	SAVA	High vegetation cover (grasses, shrubs and trees) and mostly found in the West Sudanian Savannah.
Rocky soil	SOIL_R	Non-flat areas with soils composed by stones, silt and/or clay. Usually associated to mountain regions and with sparse or no vegetation cover.
Rocky plateaus	ROPL	Flat areas totally covered by stones and located in mountain plateaus (locally known as *Hamada*). Presence of isolated *Acacia sp.* or with no vegetation.
Croplands	CROP	Areas of crop cultivation (e.g., rice and sorghum) and mostly associated to places with high water availability (e.g., near the Senegal River).
Water bodies	WATB	Permanent water features, such as rivers, lakes and mountain lagoons (locally known as *Guelta*).
Salt pans	SPAN	Large flat areas covered by salt (locally known as *Sebkha*). No vegetation cover.
Urban areas	URBA	Major cities and villages.
Roads	ROAD	Major paved roads.
Railroads	RAIL	Major railroads. The conveyor belt for phosphate transportation between Bou Craa-Layounne (Morocco) was also considered in this class.

TABLE C.3 - ***Pairwise Bhattacharyya distance between the selected 14 land-cover classes [distance varies between 0 (no separability) and 2 (full separability)]. Classes are coded as YDUN (yellow dunes), COMPS (compact sand), COMPSO (compact soil), CROP (croplands), ROPL (rocky plateaus), WDUN (white dunes), ODUN (orange dunes), GRFL (gravel floodplains), GSFL (gravel + sand floodplains), ROCK (bare rock), GRAS (grasslands), SAVA (savannah), SPAN (salt pans) and SOIL_R (rocky soil).***

	YDUN	COMPS	COMPSO	CROP	ROPL	WDUN	ODUN	GRFL	GSFL	ROCK	GRAS	SAVA	SPAN
COMPS	1.9421												
COMPSO	1.9947	1.8580*											
CROP	2.0000	1.9706	1.9905										
ROPL	1.9823	1.9988	1.6951*	1.9732									
WDUN	1.8283*	1.9922	1.9990	2.0000	1.9998								
ODUN	1.9995	1.7580*	1.9926	1.9990	1.9990	1.9996							
GRFL	1.9999	1.9998	1.9930	1.9671	1.9431	1.9999	1.9999						
GSFL	1.9999	1.9999	1.9983	1.9990	1.9967	1.9943	2.0000	1.8305*					
ROCK	1.9998	1.9985	1.9656	1.9022	1.6267*	1.9910	1.9998	1.7855*	1.9846				
GRAS	1.9943	1.7653*	1.6909*	1.8058*	1.7456*	1.9998	1.9777	1.9035	1.9897	1.6974*			
SAVA	2.0000	1.9994	1.9990	1.7509*	1.9993	2.0000	2.0000	1.9991	2.0000	1.9992	1.8692*		
SPAN	1.9999	1.9996	1.9995	1.9608	1.9832	1.9991	1.9999	1.9885	1.9997	1.9743	1.9535	1.9994	
SOIL_R	1.9313	1.9991	1.6764*	1.9990	1.9314	1.9999	1.9999	1.9997	1.9998	1.9988	1.9657	2.0000	1.9998

* classes with distance < 1.90 (no full separability but separable to some extent).

TABLE C.4 - ***Confusion matrix of post-stratified estimated proportions for the selected 14 land-cover classes1. Columns indicate the estimated proportion of validation control points/class correctly and incorrectly classified. Rows indicate the estimated proportion of control points from all the available classes that were attributed to a particular class.***

	COMPSO	SOIL_R	GRAS	ROPL	YDUN	COMPS	SPAN	SAVA	ROCK	GRFL	GSFL	ODUN	WDUN	CROP	Total (n)
COMPSO	0.155	0.019	0.018	0.001	0.001	0.003	0.000	0.000	0.001	0.001	0.000	0.001	0.000	0.000	0.201
SOIL_R	0.002	0.018	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.021
GRAS	0.010	0.001	0.063	0.001	0.002	0.000	0.000	0.001	0.004	0.003	0.000	0.000	0.000	0.001	0.086
ROPL	0.001	0.000	0.003	0.010	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.019
YDUN	0.002	0.000	0.001	0.000	0.131	0.003	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.139
COMPS	0.000	0.000	0.004	0.000	0.001	0.049	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.056
SPAN	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
SAVA	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.021	0.000	0.000	0.000	0.000	0.000	0.001	0.024
ROCK	0.000	0.000	0.006	0.003	0.000	0.000	0.000	0.000	0.055	0.005	0.000	0.000	0.000	0.000	0.069
GRFL	0.001	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.002	0.075	0.004	0.000	0.000	0.000	0.083
GSFL	0.002	0.001	0.000	0.000	0.005	0.001	0.000	0.000	0.001	0.007	0.140	0.000	0.000	0.000	0.157
ODUN	0.000	0.000	0.000	0.000	0.002	0.002	0.000	0.000	0.000	0.000	0.000	0.054	0.000	0.000	0.059
WDUN	0.000	0.000	0.000	0.000	0.009	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.070	0.000	0.080
CROP	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.003	0.005
Total (n)	0.174	0.039	0.098	0.014	0.152	0.060	0.002	0.024	0.068	0.091	0.146	0.056	0.071	0.004	

TABLE C.5 - ***Final land-cover classes, classified area, proportion of classified area (Wi) and post-stratified estimated area (SD) for the West Sahara-Sahel study area.***

Land-cover class	Area (km^2)	W_i	Estimated area (km^2)
Compact soil	346843	0.201	301011 (±11.52)
Gravel + sand floodplains	271440	0.157	252446 (±6.01)
Yellow dunes	239871	0.139	262052 (±8.5)
Grasslands	149100	0.086	169575 (±12.99)
Gravel floodplains	144179	0.083	158127 (±4.9)
White dunes	137634	0.080	122644 (±4.65)
Bare rock	119123	0.069	117215 (±4.43)
Orange dunes	102571	0.059	97221 (±1.7)
Compact sand	96444	0.056	103908 (±9.8)
Savannah	41548	0.024	41044 (±0.53)
Rocky soil	35865	0.021	67282 (±4.94)
Rocky plateaus	32466	0.019	24671 (±1.54)
Croplands	8682	0.005	7582 (±0.24)
Water bodies	3103	0.002	4091 (±0.18)
Salt pans	346843	0.201	*
Urban areas	271442	0.157	*
Roads	239871	0.139	*
Railroads	149100	0.086	*

* Classes not derived from LC classification.

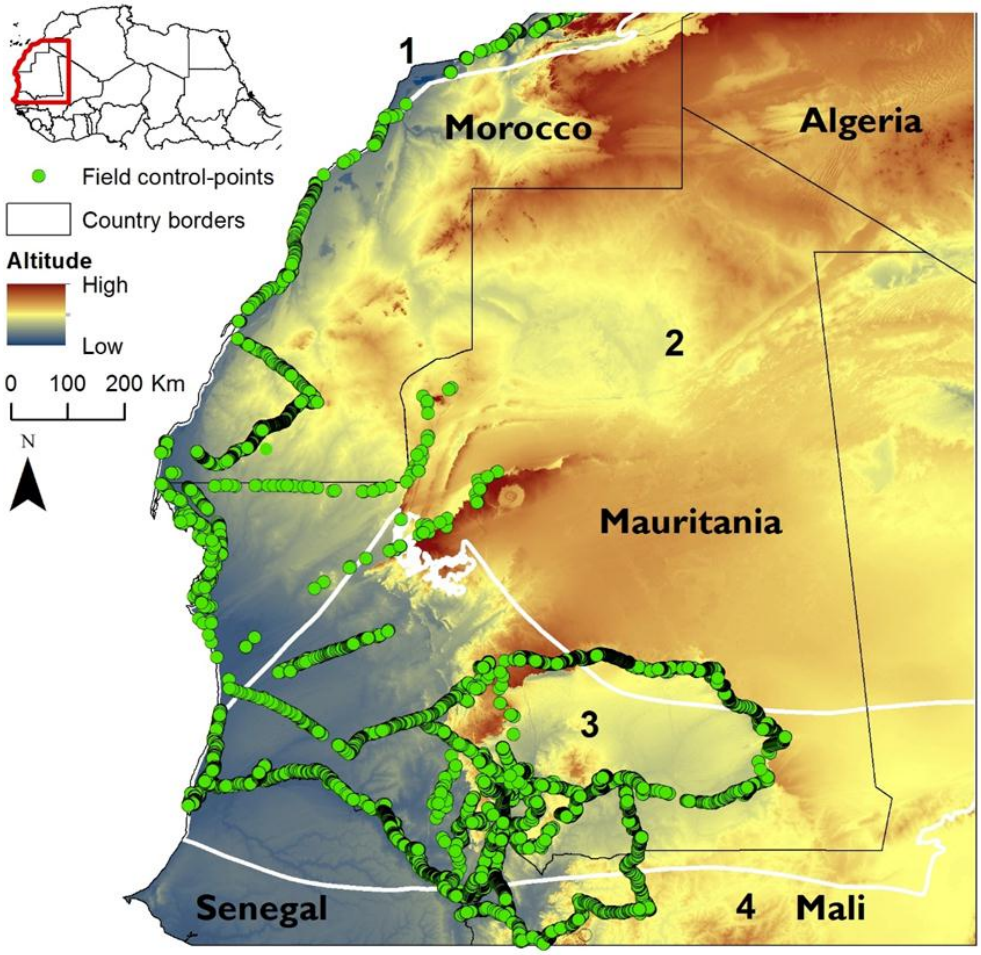

FIG. C.1 - ***Study area limits and field control-points used for the land cover classification. The study area limits were adjusted to the spatial coverage of the field control points, covering four major ecoregions (according to Olson*** **et al.** ***2001). The white lines represent the boundaries between major ecoregions and they are numerated as: 1- Mediterranean Acacia-Argania dry woodlands and succulent thickets (1% study area coverage - 21,176,648 pixels); 2- Sahara (combining the Sahara desert, the North and South Saharan steppes and woodlands, the Atlantic Coastal Desert, the West Saharan mountain xeric woodlands, and the Saharan halophytics ecoregions; 66% - 1,265,480,670 pixels); 3- Sahelian Acacia savannah (25% - 472,849,772 pixels); and 4- West Sudanian Savannah (8% - 143,901,028 pixels). The five ecoregions had significant differences of study area coverage (chi-squared test; p<0.001).***

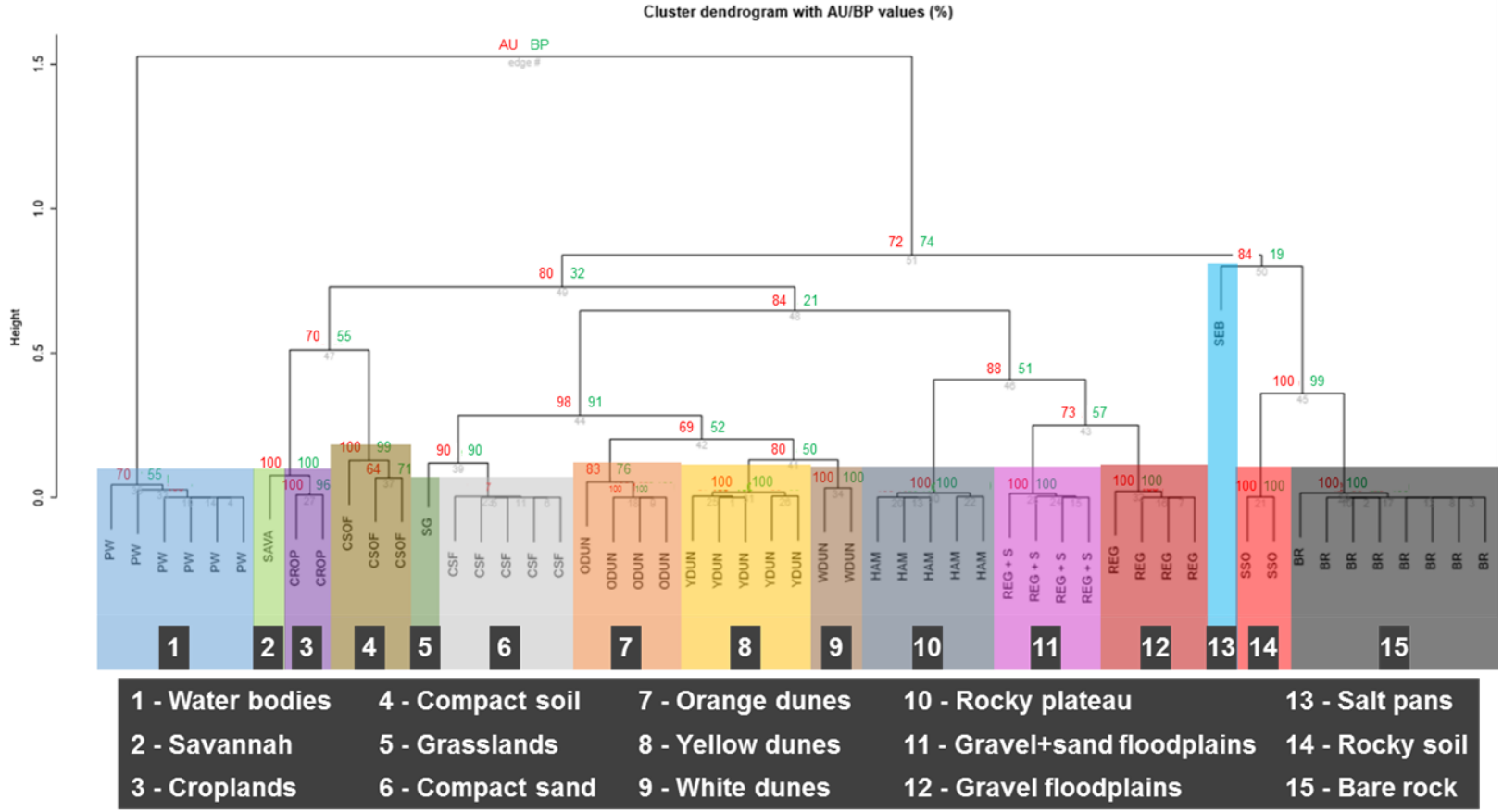

FIG. C.2 - ***Final dendrogram derived from the iterative Hierarchical Cluster Analyses (HCA) with 1000 bootstrap replicates. Clusters are highlighted with different colours, representing the numerated land-cover classes. Statistical significance of branches are indicated by the Approximately Unbiased p-value (red numbers) computed by multiscale bootstrap resampling and the Bootstrap Probability value (green numbers).***

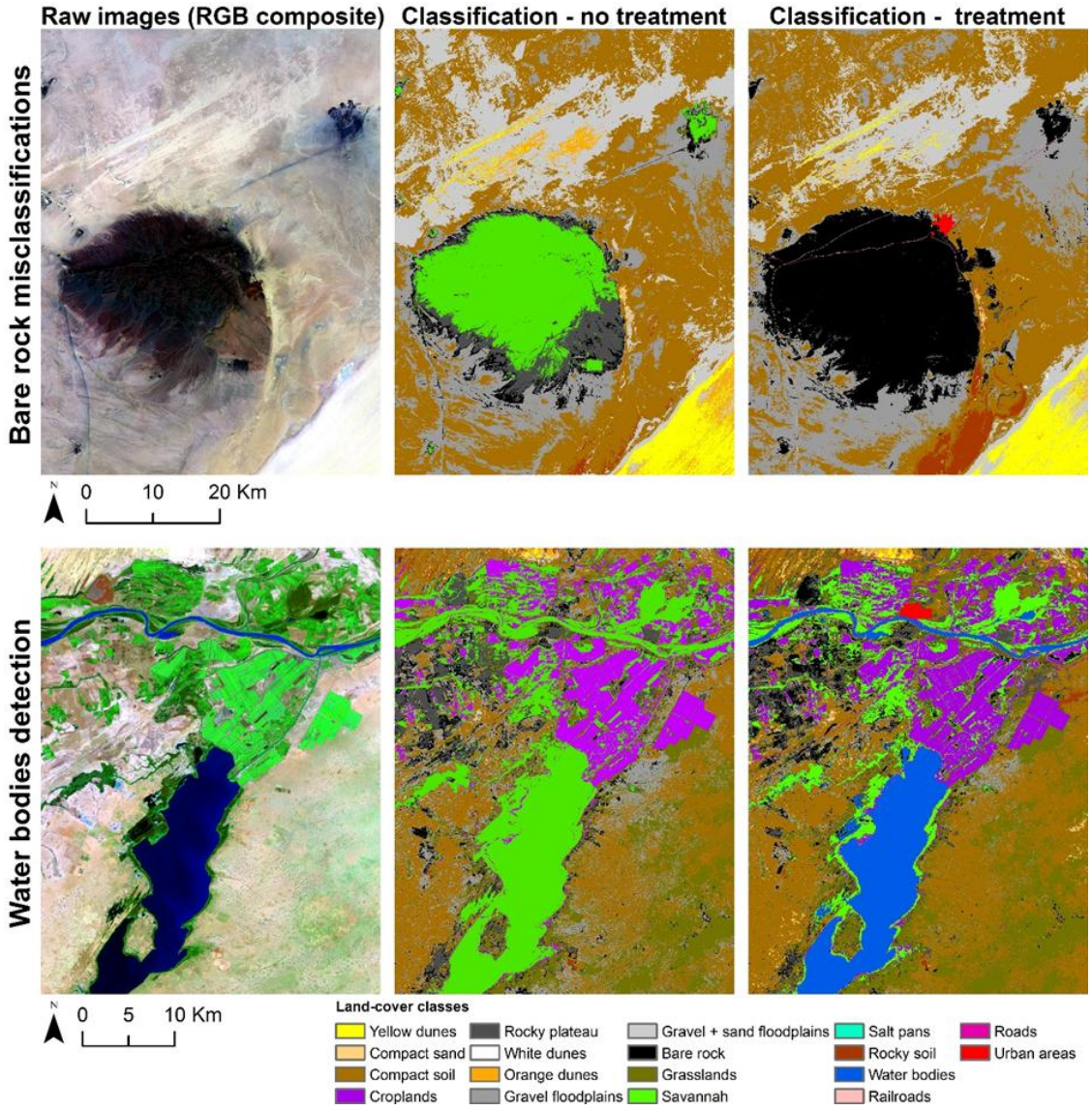

FIG. C.3 - ***Examples of classification corrections for bare rock misclassifications (upper figures) and water bodies (lower figures). For each case, a raw RGB composite mosaic (R: band 3-green; G: band 5-NIR; B: band 7-SWIR 2), a classification image before and after the treatment (application of savannah mask and AWEIsh calculation for the upper and lower examples, respectively) are presented.***

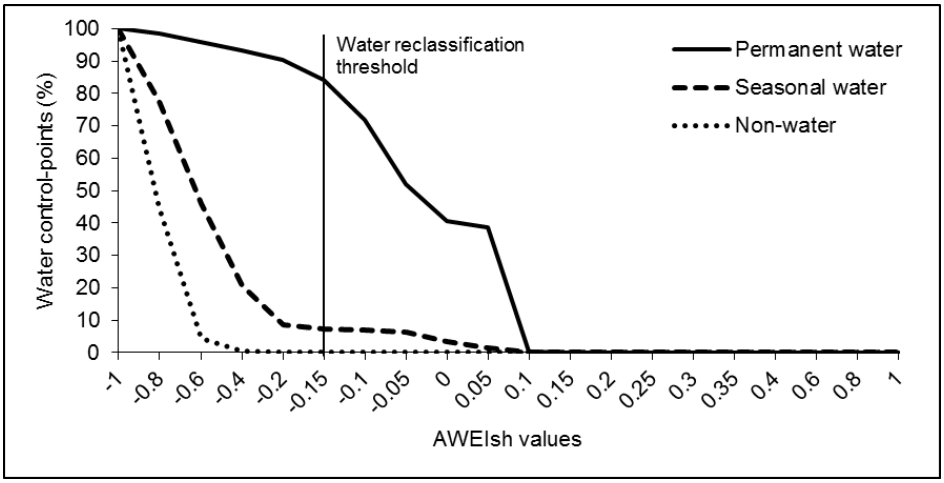

FIG. C.4 - ***Values of AWEIsh for the extracted field water control-points (%), separated in three classes: non-water points (N=3072; dotted lines), seasonal water points (N=3962; dashed lines) and permanent water points (N=1088; solid lines). The water reclassification threshold for the AWEIsh (vertical line) was defined for maximising the correct reclassification of most permanent water points and minimising the reclassification of non-water points.***

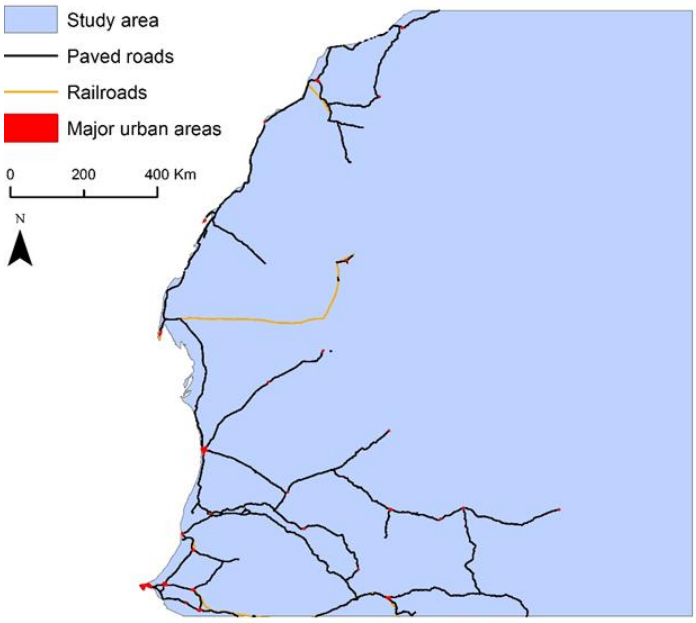

FIG. C.5 - ***Classes obtained separately from the land cover classification by field GPS-tracks (paved roads) and visual interpretation of satellite images (railroads and major urban areas).***

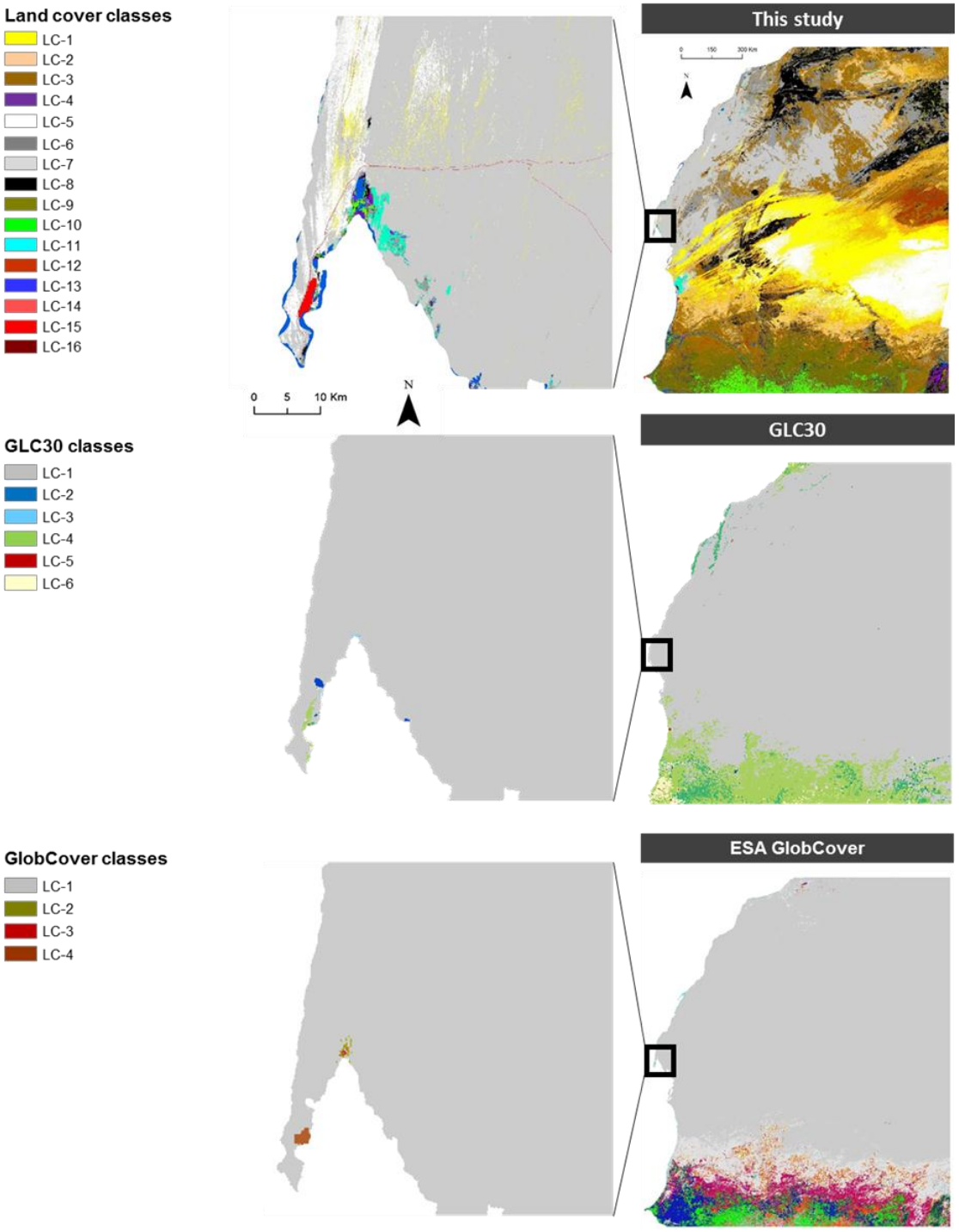

FIG. C.6 - ***Detailed visual contrasts between land cover maps derived in this study (upper map), the GLC30 (middle map) and the ESA GlobCover 2009 (lower map). Land cover classes are represented according to colours and coded as "LC-class number". Land cover class names are not indicated given its irrelevance for the visual contrast between maps. The zoom shows the land cover classification details of a coastal region in the study area (Cape Blanc, Mauritania).***

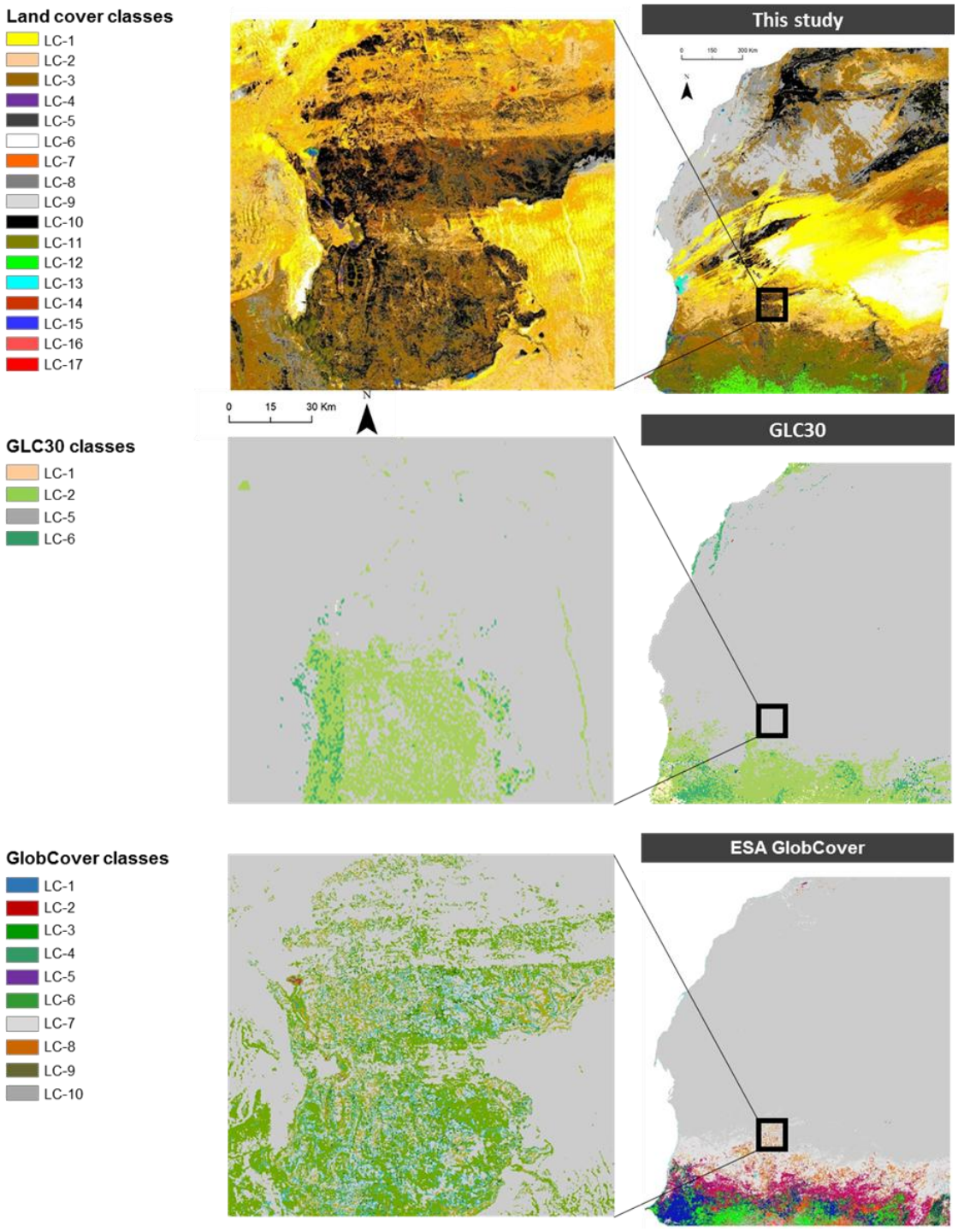

FIG. C.7 - ***Detailed visual contrasts between land cover maps derived in this study (upper map), the GLC30 (middle map) and the ESA GlobCover 2009 (lower map). Land cover classes are represented according to colours and coded as "LC-class number". Land cover class names are not indicated given its irrelevance for the visual contrast between maps. The zoom shows the land cover classification details of an inland region in the study area (Tagant mountain, Mauritania).***

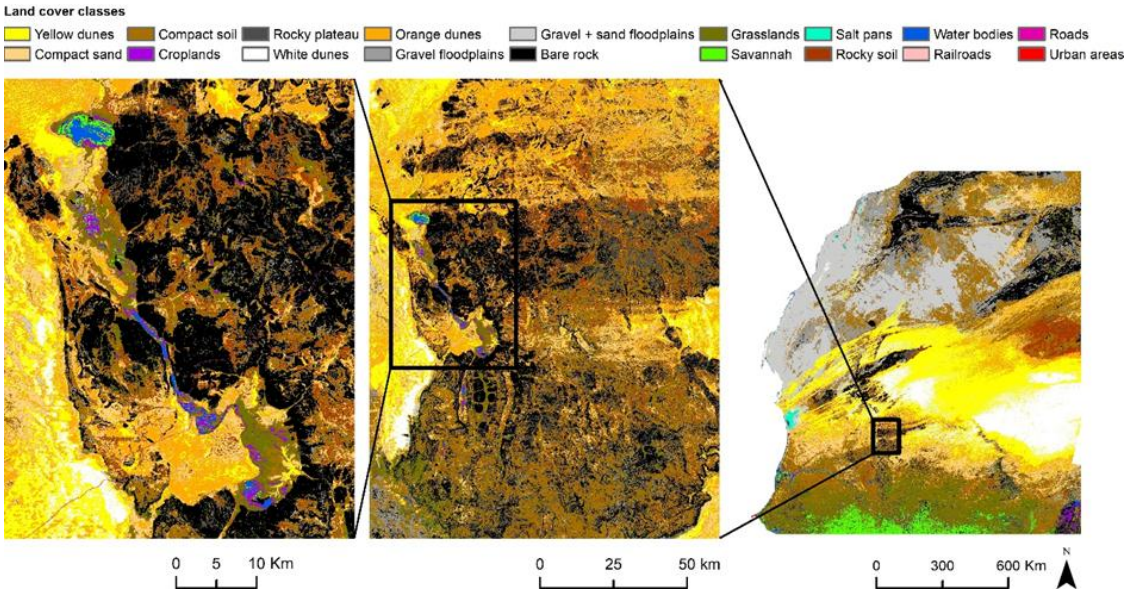

FIG. C.8 - ***Example of the detailed detection of water-bodies (mountain lagoons) included in the final land cover map. The finest zoom shows the land cover classification details of Gabbou river basin and Tâmoûrt En'Naj (Tagant mountain, Mauritania).***

APPENDIX D

Update of distribution, habitats, population size, and threat factors for the West African crocodile in Mauritania

TABLE D.1 - ***Localities considered for the threat analysis. Analyses were restricted to localities where population status was classified as "present" or "possible" and combined localities listed in Brito* et al. *(2011a) and this work. Habitat refers to the type of aquatic habitats, coded as Dam (D), Guelta (G); Lake (L); Oued (O); Source (S); and Tâmoûrt (T); Threats refers to the total number of threats identified in each location; Type of threats refers to the list of threats identified in each location (threats are coded according to the IUCN Threat Classification Scheme; see Table 6.1); Status refers to C. suchus population status coded as Present (PR) or Possible (PO); Reference mentions the publication where the location was presented and is coded as 1 (from Brito* et al. *2011a) and * (from this study).***

Locality	Habitat	Mountain	Basin	Threats	Type of threats	Status	Reference
Amzouzef	G	Tagant	Gabbou	6	2.3.1, 2.3.2, 7.2.1, 9.1.3(1), 11.2, 11.3	PR	[1]
Aouinet	G	Tagant	Gabbou	5	2.3.1, 7.2.1, 10.3, 11.2, 11.3	PO	*
Aouînet Nanâga	S	Tagant	Gorgol el Abiod	6	2.3.1, 7.2.1, 9.1.3(2), 10.3, 11.2, 11.3	PR	[1]
Ayoun el Khechba	O	Tagant	Gorgol el Abiod	2	11.2, 11.3	PO	[1]
Bâfa	O	Assaba	Gorgol el Akhdar	6	2.3.1, 2.3.2, 7.2.1, 7.2.3, 11.2, 11.3	PR	[1]
Bajai	G	Tagant	Gabbou	4	2.3.1, 7.2.1, 11.2, 11.3	PR	[1]
Bargatanni	O	Afollé	Karakoro	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PO	*
Bednam	G	Afollé	Karakoro	6	2.3.1, 2.3.2, 7.2.1, 9.1.3(1), 11.2, 11.3	PR	*

TABLE D.1 - ***Continued.***

Locality	Habitat	Mountain	Basin	Threats	Type of threats	Status	Reference
Borie, E of	O	Afollé	Kolimbiné	8	2.1.2, 2.3.1, 7.2.1, 7.2.3, 9.1.3(1), 9.3.3, 11.2, 11.3	PR	*
Bou BleïʹÎne	L	Afollé	Karakoro	5	2.3.1, 7.2.1, 7.2.3, 11.2, 11.3	PR	1
Bougâri	T	Afollé	Karakoro	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	1
Ch'Bayer	G	Tagant	Gabbou	6	2.3.1, 2.3.2, 7.2.1, 7.2.3, 11.2, 11.3	PR	1
Chegg el Mâleh	S	Afollé	Kolimbiné	5	2.3.1, 7.2.1, 9.1.3(2), 11.2, 11.3	PR	1
Daal	G	Tagant	Gabbou	5	2.3.1, 7.2.1, 9.1.3(1), 11.2, 11.3	PR	1
Djafarat	O	Afollé	Kolimbiné	5	2.3.1, 2.3.2, 7.2.1, 11.2, 11.3	PR	*
Djouk	T	Tagant	Gorgol el Abiod	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PO	1
Ederoum	D	Tagant	Gabbou	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	1
El Ghâira	S	Tagant	Gorgol el Abiod	8	2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(2), 10.3, 11.2, 11.3	PR	1
El HousseînîÿaS	S	Tagant	Gabbou	7	2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(2), 11.2, 11.3	PR	1
El Khadra	T	Afollé	El Mefga	9	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(1), 9.3.3, 11.2, 11.3	PO	*
El Khedia	G	Tagant	Gabbou	7	2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(1), 11.2, 11.3	PR	1
Borie, E of	O	Afollé	Kolimbiné	8	2.1.2, 2.3.1, 7.2.1, 7.2.3, 9.1.3(1), 9.3.3, 11.2, 11.3	PR	*

TABLE D.1 - ***Continued.***

Locality	Habitat	Mountain	Basin	Threats	Type of threats	Status	Reference
El Mefga	G	Afollé	El Mefga	7	2.3.1, 2.3.2, 7.2.1, 9.1.3(1), 10.3, 11.2, 11.3	PR	[1]
El Vouk	T	Afollé	Karakoro	5	2.3.1, 2.3.2, 7.2.1, 11.2, 11.3	PR	*
El'Atchân	O	Afollé	Karakoro	4	2.3.1, 7.2.1, 11.2, 11.3	PR	*
El-Khom Sânîyé	G	Afollé	Kolimbiné	4	2.3.1, 7.2.1, 11.2, 11.3	PR	*
Emreimida	G	Tagant	Gabbou	7	2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(1), 11.2, 11.3	PR	[1]
En Teska	O	Tagant	Gabbou	5	2.3.1, 7.2.1, 9.1.3(2), 11.2, 11.3	PO	*
E-n-Guinâr, SW of	G	Tagant	Gorgol el Abiod	5	2.3.1, 7.2.1, 9.1.3(1), 11.2, 11.3	PR	[1]
Foum Goussas	O	Assaba	Gorgol el Akhdar	5	2.3.1, 2.3.2, 7.2.1, 11.2, 11.3	PR	[1]
Gaât Sawana	T	Afollé	Kolimbiné	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	[1]
Gabbou	L	Tagant	Gabbou	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	[1]
Gâdoum	T	Afollé	Karakoro	6	2.3.1, 2.3.2, 7.2.1, 7.2.3, 11.2, 11.3	PR	[1]
Galoûla	G	Assaba	Gorgol el Akhdar	7	2.3.1, 7.2.1, 7.2.3, 9.1.3(1), 10.3, 11.2, 11.3	PR	*
Garaouel	G	Tagant	Gorgol el Abiod	6	2.3.1, 7.2.1, 9.1.3(1), 10.3, 11.2, 11.3	PR	[1]
Gharghar	T	Afollé	Kolimbiné	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	[1]
Goumbel	G	Assaba	Garfa	9	2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(1), 9.1.3(2), 10.3, 11.2, 11.3	PR	[1]
Goungel	T	Afollé	Kolimbiné	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	[1]
Guelb Samba	D	Afollé	Kolimbiné	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	[1]

TABLE D.1 - ***Continued.***

Locality	Habitat	Mountain	Basin	Threats	Type of threats	Status	Reference
Guelleït	T	Assaba	Gorgol el Akhdar	4	2.3.1, 7.2.1, 11.2, 11.3	PO	[1]
Gueltet Thor	G	Tagant	Gorgol el Abiod	6	2.3.1, 2.3.2, 7.2.1, 10.3, 11.2, 11.3	PO	[1]
Guenétir 1	T	Assaba	Garfa	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PO	[1]
Guenétir 2	S	Assaba	Garfa	3	10.3, 11.2, 11.3	PR	[1]
Guidemballa	G	Assaba	Gorgol el Akhdar	4	2.3.1, 7.2.1, 11.2, 11.3	PR	[1]
Irad, downstream of guelta	O	Tagant	Gabbou	7	2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(1), 11.2, 11.3	PR	*
Irijil El Gçerba	O	Afollé	Karakoro	6	2.3.1, 2.3.2, 7.2.1, 9.1.3(1), 11.2, 11.3	PO	*
Jabara	G	Tagant	Gabbou	4	2.3.1, 7.2.1, 11.2, 11.3	PR	[1]
Jaraaziza	T	Afollé	Karakoro	4	2.3.1, 7.2.1, 11.2, 11.3	PR	[1]
Jreif	O	Tagant	Gorgol el Abiod	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	[1]
Kabda	G	Tagant	Gabbou	3	10.3, 11.2, 11.3	PR	[1]
Kaimel	G	Tagant	Gabbou	4	2.3.1, 7.2.1, 11.2, 11.3	PR	[1]
Kankossa, SW of	L	Assaba	Karakoro	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PO	[1]
Kour	T	Afollé	El Mefga	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	[1]
Laout	G	Tagant	Gorgol el Abiod	6	2.3.1, 7.2.1, 9.1.3(1), 10.3, 11.2, 11.3	PO	[1]
Legleyta	G	Assaba	Karakoro	7	2.3.1, 7.2.1, 7.2.3, 9.1.3(1), 9.1.3(2), 11.2, 11.3	PR	[1]
Lemcherba	G	Tagant	Gabbou	4	2.3.1, 7.2.1, 11.2, 11.3	PR	[1]

TABLE D.1 - ***Continued.***

Locality	Habitat	Mountain	Basin	Threats	Type of threats	Status	Reference
Lemhara	O	Afollé	Karakoro	4	2.3.1, 7.2.1, 11.2, 11.3	PR	*
Magr'a Safia	O	Afollé	Karakoro	4	2.3.1, 7.2.1, 11.2, 11.3	PR	*
Mahmoudé	L	NA	Nioût	4	2.3.1, 7.2.1, 11.2, 11.3	PO	*
Matmâta	G	Tagant	Gabbou	6	2.3.1, 2.3.2, 7.2.1, 7.2.3, 11.2, 11.3	PR	1
M'bout, 10km N of	D	Assaba	Gorgol el Akhdar	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	*
Mechaouba	G	Afollé	Karakoro	5	2.3.1, 7.2.1, 10.3, 11.2, 11.3	PO	*
Megta es Sfeira	D	Afollé	Karakoro	9	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(2), 9.3.3, 11.2, 11.3	PR	1
Metraoucha	G	Afollé	Karakoro	5	2.3.1, 7.2.1, 10.3, 11.2, 11.3	PR	1
Meyla	G	Assaba	Garfa	3	10.3, 11.2, 11.3	PR	*
Motoboul	G	Tagant	Gabbou	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PO	1
Mreimidet El Bidâne	D	Afollé	Karakoro	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	*
Mzalig	O	Afollé	Kolimbiné	4	2.3.1, 7.2.1, 11.2, 11.3	PR	*
Mzarellit	O	Afollé	Kolimbiné	5	2.3.1, 7.2.1, 9.1.3(1), 11.2, 11.3	PR	*
Na'aj	T	Tagant	Gabbou	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	1
Oumm Lelli	T	Afollé	Kolimbiné	8	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.3.3, 11.2, 11.3	PR	1
Oumm el Mhâr	G	Afollé	Karakoro	7	2.3.1, 2.3.2, 7.2.1, 9.1.3(1), 10.3, 11.2, 11.3	PR	1
Oumm Icheglâne	S	Assaba	Koûrourai	6	2.3.1, 7.2.1, 9.1.3(2), 10.3, 11.2, 11.3	PR	1

TABLE D.1 - ***Continued.***

Locality	Habitat	Mountain	Basin	Threats	Type of threats	Status	Reference
Passes de Diégoum, 2km S of	O	Afollé	Karakoro	5	2.3.1, 2.3.2, 7.2.1, 11.2, 11.3	PR	
Rh' Zembou	G	Tagant	Gabbou	6	2.3.1, 2.3.2, 7.2.1, 9.1.3(1), 11.2, 11.3	PR	
Suklan	G	Tagant	Gabbou	4	2.3.1, 7.2.1, 11.2, 11.3	PR	
Taghtâfet	T	Afollé	Karakoro	5	2.3.1, 2.3.2, 7.2.1, 11.2, 11.3	PR	
Tâmchekket	T	Afollé	Karakoro	9	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(2), 9.3.3, 11.2, 11.3	PR	[1]
Taorta	G	Tagant	Gabbou	7	2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(1), 11.2, 11.3	PR	[1]
Tartêga	G	Tagant	Gabbou	2	11.2, 11.3	PR	[1]
Tartêga, upstream of	O	Tagant	Gabbou	5	2.3.1, 7.2.1, 9.1.3(1), 11.2, 11.3	PR	[1]
Tidâtene	T	Afollé	Karakoro	9	2.1.2, 2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(1), 9.3.3, 11.2, 11.3	PR	*
Timbâd Ed Dine	S	Afollé	Kolimbiné	5	2.3.1, 7.2.1, 10.3, 11.2, 11.3	PR	*
Tin Waadine	G	Tagant	Gabbou	8	2.3.1, 2.3.2, 7.2.1, 7.2.3, 9.1.3(1), 10.3, 11.2, 11.3	PR	[1]
Tkhsutin	G	Tagant	Gabbou	4	2.3.1, 7.2.1, 11.2, 11.3	PR	[1]

TABLE D.2 - ***New localities of C. suchus discovered in this study and previously published localities in which the crocodile status was updated (*). The locality codes correspond to the order presented in Fig. 6.1. Habitat refers to the type of aquatic habitats, coded as Dam (D), Guelta (G); Lake (L); Oued (O); Source (S); and Tâmoûrt (T); Latitude and Longitude are presented in decimal degrees (WGS84 datum); Date is related with the last observation in this study; Status refers to C. suchus population status coded as Present (PR) or Possible (PO); N mentions the maximum number of crocodiles reported.***

Code	Locality	Habitat	Latitude	Longitude	Date	Status	N
1	Gleitat Ej Jmel	G	18.400353	-11.814568	2014	PR	-
2	En Teska	O	18.397872	-11.827242	2014	PO	-
3	Niemelane	O	18.343186	-11.671342	2014	PO	-
4	Irad, downstream of guelta	O	18.258250	-11.513437	2011	PR	5
5	Aouinet	G	17.492952	-12.116253	2016	PO	-
6	El'Atchân	O	16.923777	-10.593842	2016	PR	4
7	El Vouk	T	16.903207	-10.732113	2016	PR	-
8	Bargatanni	O	16.817493	-10.740085	2016	PO	-
9	Mreimidet el Bidâne	D	16.782774	-10.746749	2016	PR	2
10	El Khadra	T	16.577108	-9.983632	2014	PO	-
11	Mahmoudé	L	16.398708	-7.665378	2014	PO	-
12	Timbâd Ed Dine	S	16.412065	-10.849448	2016	PR	-
13	Mechaouba	G	16.301168	-10.853177	2016	PO	-
14	El-Khom Sânîyé	G	16.153808	-10.752278	2016	PR	1

TABLE D.2 - ***Continued.***

Code	Locality	Habitat	Latitude	Longitude	Date	Status	N
15	Djafarat	O	16.051308	-10.544210	2014	PR	-
16	Irijil El Gçerba	O	16.022822	-10.846505	2016	PO	-
17	Tidâtene	T	16.008648	-10.929053	2016	PR	12
18	Passes de Diégoum	O	15.994760	-10.866803	2016	PO	-
19	Passes de Diégoum, 2km S of	O	15.985027	-10.877833	2016	PR	1
20	Bednam	G	15.970850	-10.901560	2016	PR	8
21	Mzalig	O	15.798355	-10.805377	2014	PR	8
22	Mzarellit	O	15.674163	-10.837277	2014	PR	-
23	Lemhara	O	15.694747	-11.237802	2014	PR	11
24	Magr'a Safia	O	15.621197	-11.289797	2014	PR	-
25	Borie, E of	O	15.543132	-11.086700	2014	PR	-
26	Meyla	G	16.002553	-11.871748	2012	PR	2
27	Galoûla*	G	16.338801	-11.978097	2012	PR	2
28	M’bout, 10km N of*	D	16.085597	-12.587687	2010	PO	-

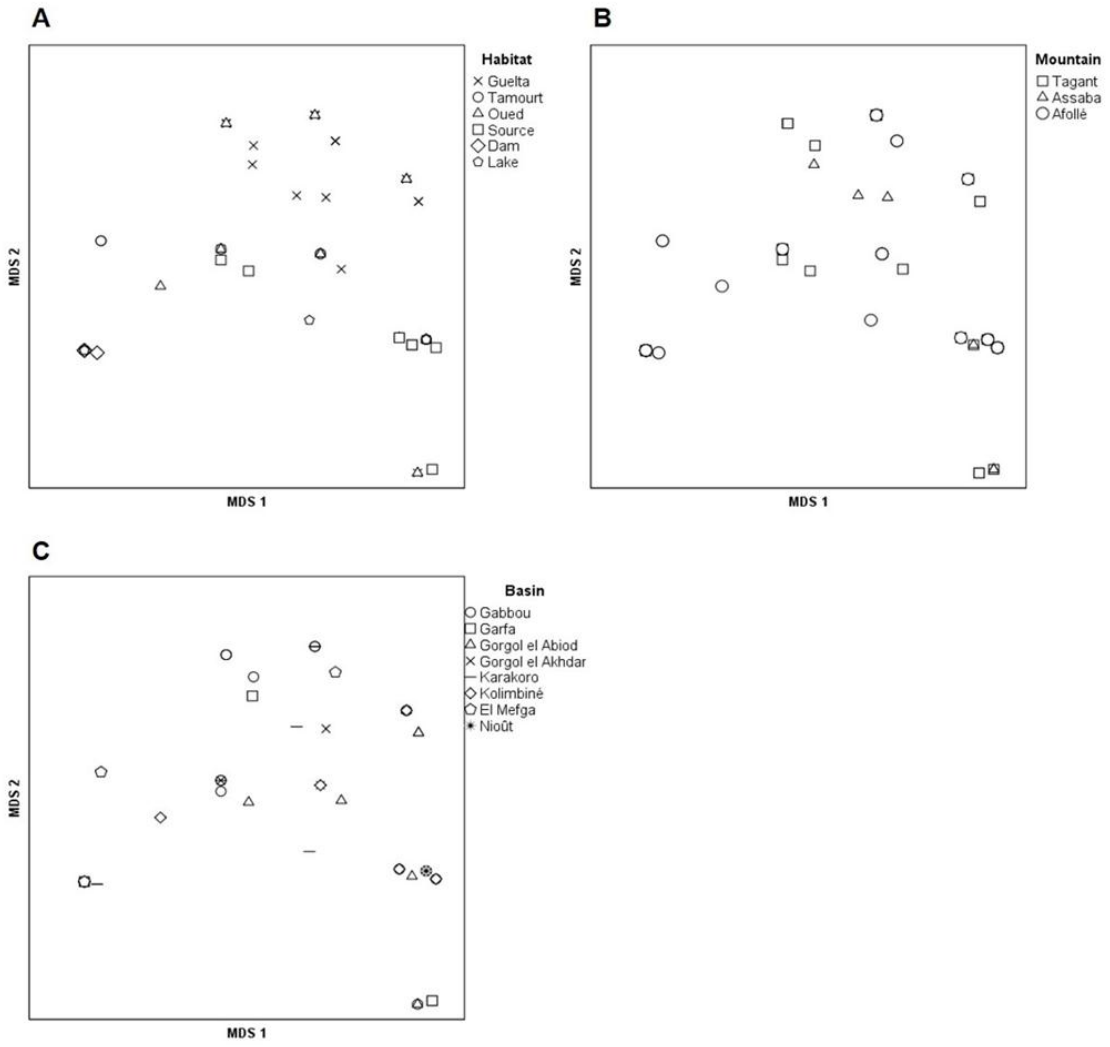

FIG. D.1 - ***Multidimensional Scaling plots derived from a distance matrix constructed using the presence/absence of the types of threats in each locality. MDS 1 and MDS 2 indicate the two dimensional axes in which the localities were ordinated. The plots represent the factors "type of habitat" (A), "mountain" (B) and hydrographical sub-basins (C).***

APPENDIX E

Unexpected strong distance effects on dispersal and population connectivity of desert crocodiles

TABLE E.1 - ***Crocodylus suchus samples analyzed in this study. The code, GPS coordinates of sample collection, country, mountain, basin, sub-basin, local, age of the individual (adult or juvenile), the fecal diameter of the scat sample (* - stands for invasive samples collected from captured individuals) and the genetic assignment at microsatellite level (genetic deme), are listed for each sample.***

Code	Latitude	Longitude	Country	Mountain	Basin	Sub-basin	Local	Age	Fecal diameter (cm)	Genetic deme
2706	17.896501	-12.126695	Mauritania	Tagant	Gabbou	Gabbou	Dar-Salam	Adult	*	Gabbou
3101	17.846378	-11.962097	Mauritania	Tagant	Gabbou	Gabbou	Kabda	Adult	2.8	Gabbou
2714	17.846344	-12.078243	Mauritania	Tagant	Gabbou	Gabbou	Bajai	Adult	2.7	Gabbou
3071	17.706072	-11.826152	Mauritania	Tagant	Gabbou	Gabbou	Amzouzef	Adult	3	Gabbou
6014	17.887298	-12.110844	Mauritania	Tagant	Gabbou	Gabbou	Matmâta	Adult	3.1	Gabbou
2688	17.887298	-12.110844	Mauritania	Tagant	Gabbou	Gabbou	Matmâta	Adult	2.9	Gabbou
3077	17.75683	-11.87492	Mauritania	Tagant	Gabbou	Gabbou	Ch'Bayer, N of	Adult	*	Gabbou
3126	17.887298	-12.110844	Mauritania	Tagant	Gabbou	Gabbou	Matmâta	Adult	2.9	Gabbou
3063	17.706072	-11.826152	Mauritania	Tagant	Gabbou	Gabbou	Amzouzef	Adult	*	Gabbou
3068	17.706072	-11.826152	Mauritania	Tagant	Gabbou	Gabbou	Amzouzef	Adult	2.9	Gabbou
3067	17.706072	-11.826152	Mauritania	Tagant	Gabbou	Gabbou	Amzouzef	Adult	2.9	Gabbou
3076	17.74163	-11.873857	Mauritania	Tagant	Gabbou	Gabbou	Rh' Zembou	Adult	*	Gabbou
12387	17.070297	-12.207848	Mauritania	Assaba	Koûrourai	Koûrourai	Oumm Icheglâne	Adult	2.7	Gabbou
12505	16.008648	-10.929053	Mauritania	Afollé	Senegal	Karakoro	Tidâtene	Adult	3.6	Karakoro

TABLE E.1 - ***Continued.***

Code	Latitude	Longitude	Country	Mountain	Basin	Sub-basin	Local	Age	Fecal diameter (cm)	Genetic deme
6103	16.57915	-10.70455	Mauritania	Afollé	Senegal	Karakoro	Oumm el Mhâr	Adult	*	Karakoro
2321	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Adult	2.8	Karakoro
2348	16.57915	-10.70455	Mauritania	Afollé	Senegal	Karakoro	Oumm el Mhâr	Adult	2.9	Karakoro
2400	16.54009	-10.80149	Mauritania	Afollé	Senegal	Karakoro	Bougâri	Adult	2.9	Karakoro
2331	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Adult	4	Karakoro
6094	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Adult	*	Karakoro
12643	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Adult	3.8	Karakoro
2322	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Adult	2.9	Karakoro
2354	16.57915	-10.70455	Mauritania	Afollé	Senegal	Karakoro	Oumm el Mhâr	Adult	*	Karakoro
6099	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Adult	2.8	Karakoro
2332	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Adult	2.9	Karakoro
2402	16.54009	-10.80149	Mauritania	Afollé	Senegal	Karakoro	Bougâri	Adult	*	Karakoro
6082	16.54009	-10.80149	Mauritania	Afollé	Senegal	Karakoro	Bougâri	Adult	*	Karakoro
6093	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Adult	*	Karakoro
6083	16.54009	-10.80149	Mauritania	Afollé	Senegal	Karakoro	Bougâri	Adult	*	Karakoro
2104	17.334838	-10.71919	Mauritania	Afollé	Senegal	Karakoro	Taghtâfet	Adult	*	Karakoro
2481	15.957078	-12.009859	Mauritania	Assaba	Senegal	Garfa	Goumbel	Adult	3.5	Karakoro
2285	16.685589	-10.179644	Mauritania	Afollé	El Mefga	El Mefga	Mefga	Adult	*	Karakoro
2317	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Adult	3.1	Karakoro

TABLE E.1 - ***Continued.***

Code	Latitude	Longitude	Country	Mountain	Basin	Sub-basin	Local	Age	Fecal diameter (cm)	Genetic deme
2397	16.54009	-10.80149	Mauritania	Afollé	Senegal	Karakoro	Bougâri	Adult	2.9	Karakoro
12701	16.782774	-10.746749	Mauritania	Afollé	Senegal	Karakoro	Mreimidet El Bidâne	Adult	2.7	Karakoro
2266	16.515562	-10.452908	Mauritania	Afollé	Senegal	Kolimbiné	Chegg el Mâleh	Adult	*	Karakoro
2399	16.54009	-10.80149	Mauritania	Afollé	Senegal	Karakoro	Bougâri	Adult	4	Karakoro
2096	17.329165	-10.708572	Mauritania	Afollé	Senegal	Karakoro	Taghtâfet	Adult	*	Karakoro
2391	16.54009	-10.80149	Mauritania	Afollé	Senegal	Karakoro	Bougâri	Adult	2.9	Karakoro
2267	16.515562	-10.452908	Mauritania	Afollé	Senegal	Kolimbiné	Chegg el Mâleh	Adult	*	Karakoro
2334	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Adult	3.3	Karakoro
11221	15.798355	-10.805377	Mauritania	Afollé	Senegal	Kolimbiné	Mzalig	Adult	*	Karakoro
11139	15.543132	-11.0867	Mauritania	Afollé	Senegal	Kolimbiné	Borie, E of	Adult	2.7	Karakoro
9582	14.9232	-9.361238	Mali	-	Senegal	Kolimbiné	Koungo	Adult	2.5	Koungo
9597	14.917935	-9.364348	Mali	-	Senegal	Kolimbiné	Koungo	Adult	*	Koungo
2514	16.184838	-12.012062	Mauritania	Assaba	Senegal	Gorgol el Akhdar	Guidemballa	Adult	2.9	Koungo
6599	16.407269	-16.334989	Mauritania	-	Senegal	Senegal	Diawling	Adult	*	Koungo
9593	14.917935	-9.364348	Mali	-	Senegal	Kolimbiné	Koungo	Adult	2.5	Koungo

TABLE E.1 - ***Continued.***

Code	Latitude	Longitude	Country	Mountain	Basin	Sub-basin	Local	Age	Fecal diameter (cm)	Genetic deme
9581	14.9232	-9.361238	Mali	-	Senegal	Kolimbiné	Koungo	Adult	2.5	Koungo
9583	14.9232	-9.361238	Mali	-	Senegal	Kolimbiné	Koungo	Adult	3	Koungo
9584	14.9232	-9.361238	Mali	-	Senegal	Kolimbiné	Koungo	Adult	2.7	Koungo
9585	14.917935	-9.364348	Mali	-	Senegal	Kolimbiné	Koungo	Adult	3	Koungo
2315	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Adult	2.8	Koungo
9592	14.917935	-9.364348	Mali	-	Senegal	Kolimbiné	Koungo	Adult	4.2	Koungo
7660	15.957078	-12.009859	Mauritania	Assaba	Senegal	Garfa	Goumbel	Adult	3.4	Gorgol el Abiod/Southern basins
3422	17.401433	-12.36415	Mauritania	Tagant	Senegal	Gorgol el Abiod	E-n-Guinâr, SW of	Adult	*	Gorgol el Abiod/Southern basins
2638	17.451667	-12.39485	Mauritania	Tagant	Senegal	Gorgol el Abiod	Garaouel	Adult	2.8	Gorgol el Abiod/Southern basins
3437	17.451667	-12.39485	Mauritania	Tagant	Senegal	Gorgol el Abiod	Garaouel	Adult	4.1	Gorgol el Abiod/Southern basins
3436	17.451667	-12.39485	Mauritania	Tagant	Senegal	Gorgol el Abiod	Garaouel	Adult	3.6	Gorgol el Abiod/Southern basins
4785	15.957078	-12.009859	Mauritania	Assaba	Senegal	Garfa	Goumbel	Adult	2.5	Gorgol el Abiod/Southern basins

TABLE E.1 - ***Continued.***

Code	Latitude	Longitude	Country	Mountain	Basin	Sub-basin	Local	Age	Fecal diameter (cm)	Genetic deme
4607	16.148812	-13.489028	Mauritania	-	Senegal	Gorgol	Kaédi	Adult	*	Gorgol el Abiod/Southern basins
3327	16.756482	-11.997233	Mauritania	Afollé	Senegal	Karakoro	Legleyta	Adult	*	Gorgol el Abiod/Southern basins
11125	15.621197	-11.289797	Mauritania	Afollé	Senegal	Karakoro	Magr'a Safia	Adult	3	Gorgol el Abiod/Southern basins
3439	17.451667	-12.39485	Mauritania	Tagant	Senegal	Gorgol el Abiod	Garaouel	Adult	2.9	Gorgol el Abiod/Southern basins
11084	15.694747	-11.237802	Mauritania	Afollé	Senegal	Karakoro	Lemhara	Adult	*	Gorgol el Abiod/Southern basins
11285	16.16076	-10.375173	Mauritania	Afollé	Senegal	Kolimbiné	Gharghar	Adult	2.9	Gorgol el Abiod/Southern basins
10361	16.39927	-16.247842	Senegal	-	Senegal	Senegal	East Gainth	Adult	3.1	Gorgol el Abiod/Southern basins
11140	15.543132	-11.0867	Mauritania	Afollé	Senegal	Kolimbiné	Borie, E of	Adult	3	Gorgol el Abiod/Southern basins
2480	15.957078	-12.009859	Mauritania	Assaba	Senegal	Garfa	Goumbel	Adult	2.8	Gorgol el Abiod/Southern basins

TABLE E.1 - ***Continued.***

Code	Latitude	Longitude	Country	Mountain	Basin	Sub-basin	Local	Age	Fecal diameter (cm)	Genetic deme
11128	15.621197	-11.289797	Mauritania	Afollé	Senegal	Karakoro	Magr'a Safia	Adult	2.5	Gorgol el Abiod/Southern basins
1417	17.401433	-12.36415	Mauritania	Tagant	Senegal	Gorgol el Abiod	E-n-Guinâr, SW of	Juvenile	2	Gabbou/Gorgol el Abiod
4878	17.152482	-12.199115	Mauritania	Tagant	Senegal	Gorgol el Abiod	Aouînet Nanâga	Juvenile	*	Gabbou/Gorgol el Abiod
2604	17.401433	-12.36415	Mauritania	Tagant	Senegal	Gorgol el Abiod	E-n-Guinâr, SW of	Juvenile	2.2	Gabbou/Gorgol el Abiod
3103	17.846378	-11.962097	Mauritania	Tagant	Gabbou	Gabbou	Kabda	Juvenile	1.7	Gabbou/Gorgol el Abiod
12266	17.887298	-12.110844	Mauritania	Tagant	Gabbou	Gabbou	Matmâta	Juvenile	2	Gabbou/Gorgol el Abiod
6015	17.887298	-12.110844	Mauritania	Tagant	Gabbou	Gabbou	Matmâta	Juvenile	2	Gabbou/Gorgol el Abiod
6114	17.152482	-12.199115	Mauritania	Tagant	Senegal	Gorgol el Abiod	Aouînet Nanâga	Juvenile	<1	Gabbou/Gorgol el Abiod
3084a	17.762083	-11.882833	Mauritania	Tagant	Gabbou	Gabbou	Ch'Bayer	Juvenile	<1	Gabbou/Gorgol el Abiod

TABLE E.1 - ***Continued.***

Code	Latitude	Longitude	Country	Mountain	Basin	Sub-basin	Local	Age	Fecal diameter (cm)	Genetic deme
6060	18.25825	-11.513437	Mauritania	Tagant	Gabbou	Gabbou	Irad, downstream of guelta	Juvenile	<1	Gabbou/Gorgol el Abiod
3085	17.762083	-11.882833	Mauritania	Tagant	Gabbou	Gabbou	Ch'Bayer	Juvenile	2	Gabbou/Gorgol el Abiod
3135	17.855314	-12.068843	Mauritania	Tagant	Gabbou	Gabbou	Lemcherba	Juvenile	2.1	Gabbou/Gorgol el Abiod
6117	17.152482	-12.199115	Mauritania	Tagant	Senegal	Gorgol el Abiod	Aouînet Nanâga	Juvenile	*	Gabbou/Gorgol el Abiod
6116	17.152482	-12.199115	Mauritania	Tagant	Senegal	Gorgol el Abiod	Aouînet Nanâga	Juvenile	*	Gabbou/Gorgol el Abiod
2687	17.887298	-12.110844	Mauritania	Tagant	Gabbou	Gabbou	Matmâta	Juvenile	1.2	Gabbou/Gorgol el Abiod
2642	17.451667	-12.39485	Mauritania	Tagant	Senegal	Gorgol el Abiod	Garaouel	Juvenile	*	Gabbou/Gorgol el Abiod
2692	17.887298	-12.110844	Mauritania	Tagant	Gabbou	Gabbou	Matmâta	Juvenile	2.1	Gabbou/Gorgol el Abiod
3368	17.070297	-12.207848	Mauritania	Tagant	Koûrourai	Koûrourai	Oumm Icheglâne	Juvenile	*	Gabbou/Gorgol el Abiod

TABLE E.1 - ***Continued.***

Code	Latitude	Longitude	Country	Mountain	Basin	Sub-basin	Local	Age	Fecal diameter (cm)	Genetic deme
2588	16.888725	-12.184868	Mauritania	Tagant	Senegal	Gorgol el Akhdar	Bâfa	Juvenile	*	Gabbou/Gorgol el Abiod
3084b	17.762083	-11.882833	Mauritania	Tagant	Gabbou	Gabbou	Ch'Bayer	Juvenile	<1	Gabbou/Gorgol el Abiod
2284	16.687579	-10.191363	Mauritania	Afollé	El Mefga	El Mefga	El Mefga	Juvenile	0.4	Karakoro
2349	16.57915	-10.70455	Mauritania	Afollé	Senegal	Karakoro	Oumm el Mhâr	Juvenile	1.7	Karakoro
2313	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Juvenile	2.3	Karakoro
2351	16.57915	-10.70455	Mauritania	Afollé	Senegal	Karakoro	Oumm el Mhâr	Juvenile	2	Karakoro
1367	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Juvenile	2	Karakoro
2287	16.687579	-10.191363	Mauritania	Afollé	El Mefga	El Mefga	El Mefga	Juvenile	*	Karakoro
12671	16.57915	-10.70455	Mauritania	Afollé	Senegal	Karakoro	Oumm el Mhâr	Juvenile	1.8	Karakoro
2374	16.57915	-10.70455	Mauritania	Afollé	Senegal	Karakoro	Oumm el Mhâr	Juvenile	*	Karakoro
2273	16.701802	-10.183587	Mauritania	Afollé	El Mefga	El Mefga	Kour	Juvenile	1.7	Karakoro
2395	16.54009	-10.80149	Mauritania	Afollé	Senegal	Karakoro	Bougâri	Juvenile	2.3	Karakoro
2286	16.687579	-10.191363	Mauritania	Afollé	El Mefga	El Mefga	El Mefga	Juvenile	*	Karakoro
12713	16.903207	-10.732113	Mauritania	Afollé	Senegal	Karakoro	El Vouk	Juvenile	1.8	Karakoro
2316	16.538033	-10.74155	Mauritania	Afollé	Senegal	Karakoro	Metraoucha	Juvenile	1.5	Karakoro
976	16.5158	-10.452483	Mauritania	Afollé	Senegal	Kolimbiné	Chegg el Mâleh	Juvenile	*	Karakoro

TABLE E.1 - ***Continued.***

Code	Latitude	Longitude	Country	Mountain	Basin	Sub-basin	Local	Age	Fecal diameter (cm)	Genetic deme
12687	16.54009	-10.80149	Mauritania	Afollé	Senegal	Karakoro	Bougâri	Juvenile	2	Karakoro
11287	16.16076	-10.375173	Mauritania	Afollé	Senegal	Kolimbiné	Gharghar	Juvenile	1.6	Karakoro
2350	16.57915	-10.70455	Mauritania	Afollé	Senegal	Karakoro	Oumm el Mhâr	Juvenile	2.3	Karakoro
11206	15.798355	-10.805377	Mauritania	Afollé	Senegal	Kolimbiné	Mzalig	Juvenile	<1	Southern basins/Koungo
12547	15.97085	-10.90156	Mauritania	Afollé	Senegal	Karakoro	Bednam	Juvenile	1.8	Southern basins/Koungo
11202	15.798355	-10.805377	Mauritania	Afollé	Senegal	Kolimbiné	Mzalig	Juvenile	<1	Southern basins/Koungo
11067	15.694747	-11.237802	Mauritania	Afollé	Senegal	Karakoro	Lemhara	Juvenile	<1	Southern basins/Koungo
11208	15.798355	-10.805377	Mauritania	Afollé	Senegal	Kolimbiné	Mzalig	Juvenile	<1	Southern basins/Koungo
11200	15.798355	-10.805377	Mauritania	Afollé	Senegal	Kolimbiné	Mzalig	Juvenile	1.5	Southern basins/Koungo
11061	15.694747	-11.237802	Mauritania	Afollé	Senegal	Karakoro	Lemhara	Juvenile	1.7	Southern basins/Koungo
11213	15.798355	-10.805377	Mauritania	Afollé	Senegal	Kolimbiné	Mzalig	Juvenile	2	Southern basins/Koungo

TABLE E.1 - ***Continued.***

Code	Latitude	Longitude	Country	Mountain	Basin	Sub-basin	Local	Age	Fecal diameter (cm)	Genetic deme
11068	15.694747	-11.237802	Mauritania	Afollé	Senegal	Karakoro	Lemhara	Juvenile	2.2	Southern basins/Koungo
7734	16.002553	-11.871748	Mauritania	Assaba	Senegal	Garfa	Meyla	Juvenile	1.7	Southern basins/Koungo
7733	16.002553	-11.871748	Mauritania	Assaba	Senegal	Garfa	Meyla	Juvenile	<1	Southern basins/Koungo
11289	16.16076	-10.375173	Mauritania	Afollé	Senegal	Kolimbiné	Gharghar	Juvenile	<1	Southern basins/Koungo
9586	14.917935	-9.364348	Mali	-	Senegal	Kolimbiné	Koungo	Juvenile	1.6	Southern basins/Koungo
9587	14.917935	-9.364348	Mali	-	Senegal	Kolimbiné	Koungo	Juvenile	1.7	Southern basins/Koungo
9588	14.917935	-9.364348	Mali	-	Senegal	Kolimbiné	Koungo	Juvenile	2	Southern basins/Koungo
11204	15.798355	-10.805377	Mauritania	Afollé	Senegal	Kolimbiné	Mzalig	Juvenile	<1	Southern basins/Koungo
12581	16.153808	-10.752278	Mauritania	Afollé	Senegal	Kolimbiné	El-Khom Sânîyé	Juvenile	0.7	Southern basins/Koungo
10674	16.342523	-16.397972	Mauritania	-	Senegal	Senegal	Bell	Juvenile	1.9	Senegal River/Garfa

TABLE E.1 - ***Continued.***

Code	Latitude	Longitude	Country	Mountain	Basin	Sub-basin	Local	Age	Fecal diameter (cm)	Genetic deme
12870	16.361683	-16.34175	Mauritania	-	Senegal	Senegal	Diawling	Juvenile	0.7	Senegal River/Garfa
12872	16.361683	-16.34175	Mauritania	-	Senegal	Senegal	Diawling	Juvenile	0.6	Senegal River/Garfa
7388	16.34594	-16.345075	Mauritania	-	Senegal	Senegal	Diawling	Juvenile	<1	Senegal River/Garfa
12879	16.361683	-16.34175	Mauritania	-	Senegal	Senegal	Diawling	Juvenile	1.2	Senegal River/Garfa
11123	15.621197	-11.289797	Mauritania	Afollé	Senegal	Karakoro	Magr'a Safia	Juvenile	1.1	Senegal River/Garfa
4629	16.085597	-12.587687	Mauritania	Afollé	Senegal	Gorgol el Akhdar	Mbout, 10km N of	Juvenile	*	Senegal River/Garfa
12874	16.361683	-16.34175	Mauritania	-	Senegal	Senegal	Diawling	Juvenile	<1	Senegal River/Garfa
2476	15.957078	-12.009859	Mauritania	Assaba	Senegal	Garfa	Goumbel	Juvenile	1.1	Senegal River/Garfa
2475	15.957078	-12.009859	Mauritania	Assaba	Senegal	Garfa	Goumbel	Juvenile	1.6	Senegal River/Garfa
11124	15.621197	-11.289797	Mauritania	Afollé	Senegal	Karakoro	Magr'a Safia	Juvenile	<1	Senegal River/Garfa

TABLE E.2 - ***Satellite images used in this study (n=91). The ID, satellite, spatial information (path and row), temporal information (date acquired) and the connectivity analyzes in which they were included (contemporary or historical connectivity analyzes) are listed for each satellite scene.***

Landsat scene ID	Satellite	Path	Row	Date acquired	Connectivity analysis
LC82000502013287LGN00	Landsat 8	200	50	14/10/2013	Contemporary connectivity
LC82000502014290LGN00	Landsat 8	200	50	17/10/2014	Contemporary connectivity
LC82000502015309LGN00	Landsat 8	200	50	05/11/2015	Contemporary connectivity
LC82000502016248LGN00	Landsat 8	200	50	04/09/2016	Contemporary connectivity
LC82000512013319LGN00	Landsat 8	200	51	15/11/2013	Contemporary connectivity
LC82000512014306LGN00	Landsat 8	200	51	02/11/2014	Contemporary connectivity
LC82000512015309LGN00	Landsat 8	200	51	05/11/2015	Contemporary connectivity
LC82000512016280LGN00	Landsat 8	200	51	06/10/2016	Contemporary connectivity
LC82010482013342LGN00	Landsat 8	201	48	08/12/2013	Contemporary connectivity
LC82010482014297LGN00	Landsat 8	201	48	24/10/2014	Contemporary connectivity
LC82010482015284LGN00	Landsat 8	201	48	11/10/2015	Contemporary connectivity
LC82010482016271LGN00	Landsat 8	201	48	27/09/2016	Contemporary connectivity
LC82010492013342LGN00	Landsat 8	201	49	08/12/2013	Contemporary connectivity
LC82010492014297LGN00	Landsat 8	201	49	24/10/2014	Contemporary connectivity
LC82010492015268LGN00	Landsat 8	201	49	25/09/2015	Contemporary connectivity
LC82010492016287LGN00	Landsat 8	201	49	13/10/2016	Contemporary connectivity
LC82010502013342LGN00	Landsat 8	201	50	08/12/2013	Contemporary connectivity
LC82010502014361LGN00	Landsat 8	201	50	27/12/2014	Contemporary connectivity
LC82010502016287LGN00	Landsat 8	201	50	13/10/2016	Contemporary connectivity
LC82010512013342LGN00	Landsat 8	201	51	08/12/2013	Contemporary connectivity
LC82010512014281LGN00	Landsat 8	201	51	08/10/2014	Contemporary connectivity
LC82010512016287LGN00	Landsat 8	201	51	13/10/2016	Contemporary connectivity
LC82020472013285LGN00	Landsat 8	202	47	12/10/2013	Contemporary connectivity
LC82020472014304LGN00	Landsat 8	202	47	31/10/2014	Contemporary connectivity
LC82020472015259LGN00	Landsat 8	202	47	16/09/2015	Contemporary connectivity
LC82020472016278LGN00	Landsat 8	202	47	04/10/2016	Contemporary connectivity
LC82020482013285LGN00	Landsat 8	202	48	12/10/2013	Contemporary connectivity
LC82020482014304LGN00	Landsat 8	202	48	31/10/2014	Contemporary connectivity
LC82020482015323LGN00	Landsat 8	202	48	19/11/2015	Contemporary connectivity
LC82020482016294LGN00	Landsat 8	202	48	20/10/2016	Contemporary connectivity
LC82020492013317LGN00	Landsat 8	202	49	13/11/2013	Contemporary connectivity
LC82020492014304LGN00	Landsat 8	202	49	31/10/2014	Contemporary connectivity
LC82020492015339LGN00	Landsat 8	202	49	05/12/2015	Contemporary connectivity

TABLE E.2 - ***Continued.***

Landsat scene ID	Satellite	Path	Row	Date acquired	Connectivity analysis
LC82020492016278LGN00	Landsat 8	202	49	04/10/2016	Contemporary connectivity
LC82020502013317LGN00	Landsat 8	202	50	13/11/2013	Contemporary connectivity
LC82020502014304LGN00	Landsat 8	202	50	31/10/2014	Contemporary connectivity
LC82020502015275LGN00	Landsat 8	202	50	02/10/2015	Contemporary connectivity
LC82020502016278LGN00	Landsat 8	202	50	04/10/2016	Contemporary connectivity
LC82030472013276LGN00	Landsat 8	203	47	03/10/2013	Contemporary connectivity
LC82030472014279LGN00	Landsat 8	203	47	06/10/2014	Contemporary connectivity
LC82030472015282LGN00	Landsat 8	203	47	09/10/2015	Contemporary connectivity
LC82030472016285LGN00	Landsat 8	203	47	11/10/2016	Contemporary connectivity
LC82030482013276LGN00	Landsat 8	203	48	03/10/2013	Contemporary connectivity
LC82030482014263LGN00	Landsat 8	203	48	20/09/2014	Contemporary connectivity
LC82030482015314LGN00	Landsat 8	203	48	10/11/2015	Contemporary connectivity
LC82030482016285LGN00	Landsat 8	203	48	11/10/2016	Contemporary connectivity
LC82030492013276LGN00	Landsat 8	203	49	03/10/2013	Contemporary connectivity
LC82030492014295LGN00	Landsat 8	203	49	22/10/2014	Contemporary connectivity
LC82030492015314LGN00	Landsat 8	203	49	10/11/2015	Contemporary connectivity
LC82030492016285LGN00	Landsat 8	203	49	11/10/2016	Contemporary connectivity
LC82040482013283LGN00	Landsat 8	204	48	10/10/2013	Contemporary connectivity
LC82040482014270LGN00	Landsat 8	204	48	27/09/2014	Contemporary connectivity
LC82040482015257LGN00	Landsat 8	204	48	14/09/2015	Contemporary connectivity
LC82040482016276LGN00	Landsat 8	204	48	02/10/2016	Contemporary connectivity
LC82040492013283LGN00	Landsat 8	204	49	10/10/2013	Contemporary connectivity
LC82040492014286LGN00	Landsat 8	204	49	13/10/2014	Contemporary connectivity
LC82040492015305LGN00	Landsat 8	204	49	01/11/2015	Contemporary connectivity
LC82040492016276LGN00	Landsat 8	204	49	02/10/2016	Contemporary connectivity
LC82050482013274LGN00	Landsat 8	205	48	01/10/2013	Contemporary connectivity
LC82050482014309LGN00	Landsat 8	205	48	05/11/2014	Contemporary connectivity
LC82050482015328LGN00	Landsat 8	205	48	24/11/2015	Contemporary connectivity
LC82050482016331LGN00	Landsat 8	205	48	26/11/2016	Contemporary connectivity
LC82050492013338LGN00	Landsat 8	205	49	04/12/2013	Contemporary connectivity
LC82050492014293LGN00	Landsat 8	205	49	20/10/2014	Contemporary connectivity
LC82050492015312LGN00	Landsat 8	205	49	08/11/2015	Contemporary connectivity
LC82050492016283LGN00	Landsat 8	205	49	09/10/2016	Contemporary connectivity
LT52000501987312MPS00	Landsat 5	200	50	08/11/1987	Historical connectivity
LT52000511987312MPS00	Landsat 5	200	51	08/11/1987	Historical connectivity
LT42010481987343XXX03	Landsat 4	201	48	09/12/1987	Historical connectivity

TABLE E.2 - ***Continued.***

Landsat scene ID	Satellite	Path	Row	Date acquired	Connectivity analysis
LT52010491984295XXX01	Landsat 5	201	49	21/10/1984	Historical connectivity
LT52010501987335MPS00	Landsat 5	201	50	01/12/1987	Historical connectivity
LT52010511987287XXX03	Landsat 5	201	51	14/10/1987	Historical connectivity
LT52020471987310MPS00	Landsat 5	202	47	06/11/1987	Historical connectivity
LT52020481984222AAA03	Landsat 5	202	48	09/08/1984	Historical connectivity
LT52020481987310MPS00	Landsat 5	202	48	06/11/1987	Historical connectivity
LT52020491987310MPS00	Landsat 5	202	49	06/11/1987	Historical connectivity
LT52020501984238XXX03	Landsat 5	202	50	25/08/1984	Historical connectivity
LT52030471987317MPS00	Landsat 5	203	47	13/11/1987	Historical connectivity
LT52030481987349MPS00	Landsat 5	203	48	15/12/1987	Historical connectivity
LT52030491984293XXX02	Landsat 5	203	49	19/10/1984	Historical connectivity
LT52030491986330XXX01	Landsat 5	203	49	26/11/1986	Historical connectivity
LT52030491987333MPS00	Landsat 5	203	49	29/11/1987	Historical connectivity
LT52040481984300XXX01	Landsat 5	204	48	26/10/1984	Historical connectivity
LT52040481987308MPS00	Landsat 5	204	48	04/11/1987	Historical connectivity
LT52040491987292XXX03	Landsat 5	204	49	19/10/1987	Historical connectivity
LT52050481984291XXX02	Landsat 5	205	48	17/10/1984	Historical connectivity
LT52050481986280XXX01	Landsat 5	205	48	07/10/1986	Historical connectivity
LT52050481987283XXX09	Landsat 5	205	48	10/10/1987	Historical connectivity
LT52050491984291XXX03	Landsat 5	205	49	17/10/1984	Historical connectivity
LT52050491986296XXX01	Landsat 5	205	49	23/10/1986	Historical connectivity
LT52050491987283XXX04	Landsat 5	205	49	10/10/1987	Historical connectivity

TABLE E.3 - ***Scenarios established for testing the isolation by landscape resistance hypothesis. For each scenario, the resistance values attributed to the variables and the rationale behind each case are presented. Spatial representation is available in Fig. E.4.***

Landscape resistance scenarios	Resistance values	Rationale
Water	Permanent and seasonal water=1; non-water=10	Water is crucial for crocodile dispersal irrespectively of its seasonality; non-water pixels surrounding permanent water pixels are highly resistant to dispersal movements
Water seasonality	Permanent water=1; seasonal water=5; non-water=10	Permanent water, due to the higher spatial and temporal availability, facilitates crocodile dispersal in comparison to seasonal water; neighboring non-water pixels are highly resistant to dispersal movements

TABLE E.4 - ***Threshold validation results for contemporary seasonal and permanent water. The results are presented by the proportion of points classified as seasonal and permanent water (n/200), according to the selected thresholds, for the three classes of water availability (non-water, seasonal and permanent water).***

	Non-water	Seasonal water	Permanent water
Seasonal water threshold (NDWI1 ≥ 0)	0/200 (0%)	164/200 (82%)	192 (96%)
Permanent water threshold (MNDWI ≥ 0)	0/200 (0%)	1/200 (0.5%)	158/200 (79%)

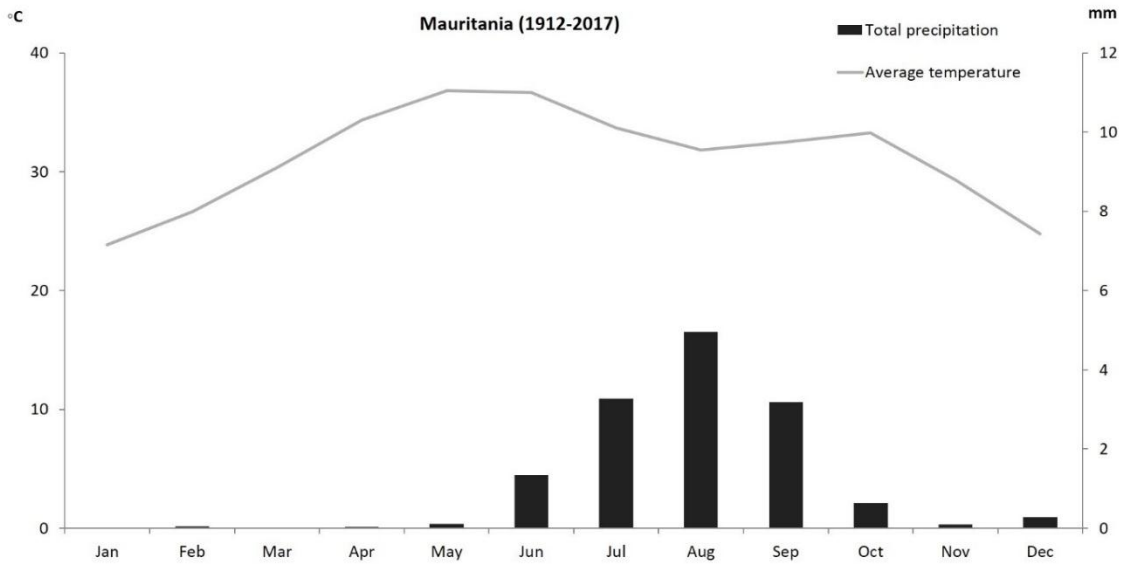

FIG. E.1 - ***Monthly total precipitation and average temperature in Mauritania between 1912 and 2017. Precipitation and temperature data were processed by the Climate Research Unit of University of East Anglia (Jones and Harris 2013) and extracted from the Climate Change Knowledge Portal of the World Bank Group (http://sdwebx.worldbank.org/climateportal/index.cfm).***

References

Jones PD, Harris IC (2013). CRU TS3.21: Climatic Research Unit (CRU) Time-Series (TS) Version 3.21 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901- Dec. 2012). NCAS British Atmospheric Data Centre.

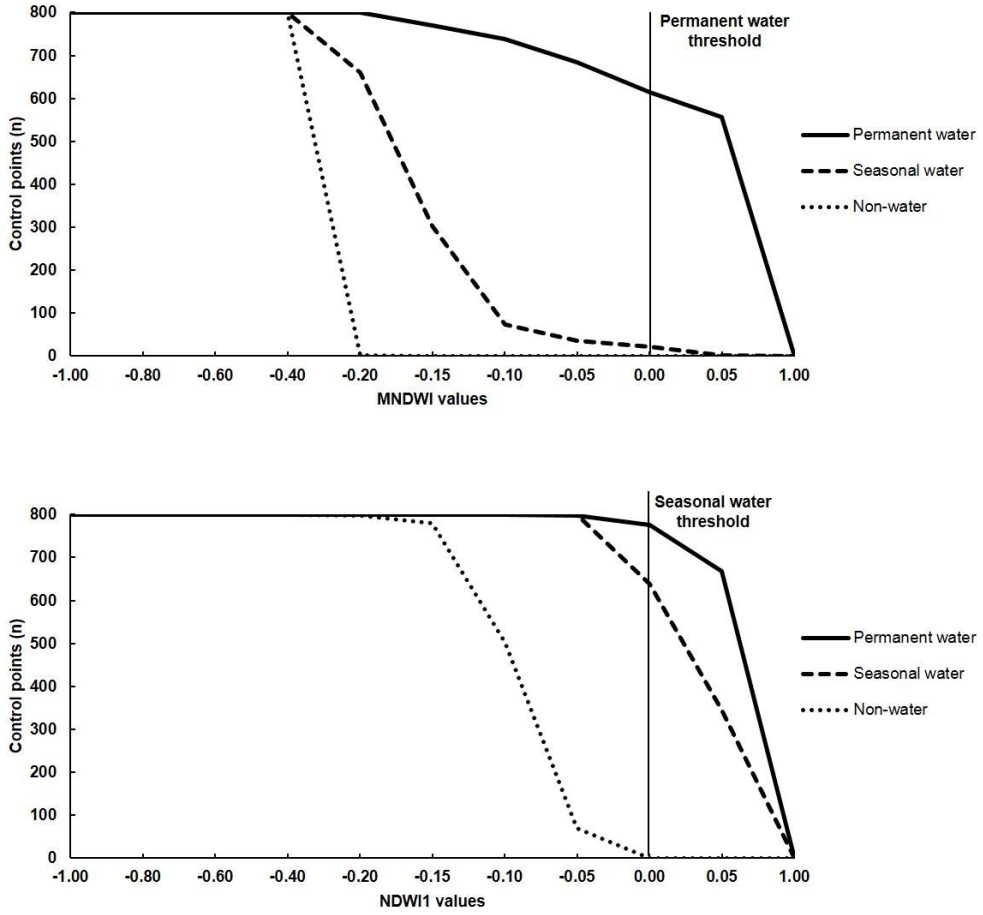

FIG. E.2 - ***Threshold selection for seasonal and permanent water reclassification. The plots show the values of MNDWI (plot on the top) and NDWI1 (plot on the bottom) for the extracted field control points used in the threshold selection (n=2400). The points are separated in three classes: non-water points (n=800; dotted lines), seasonal water points (n=800; dashed lines) and permanent water points (N=800; solid lines). The permanent/seasonal water reclassification thresholds (vertical lines) were selected for maximizing the correct reclassification of most permanent/seasonal water points and minimizing the reclassification of non-water points.***

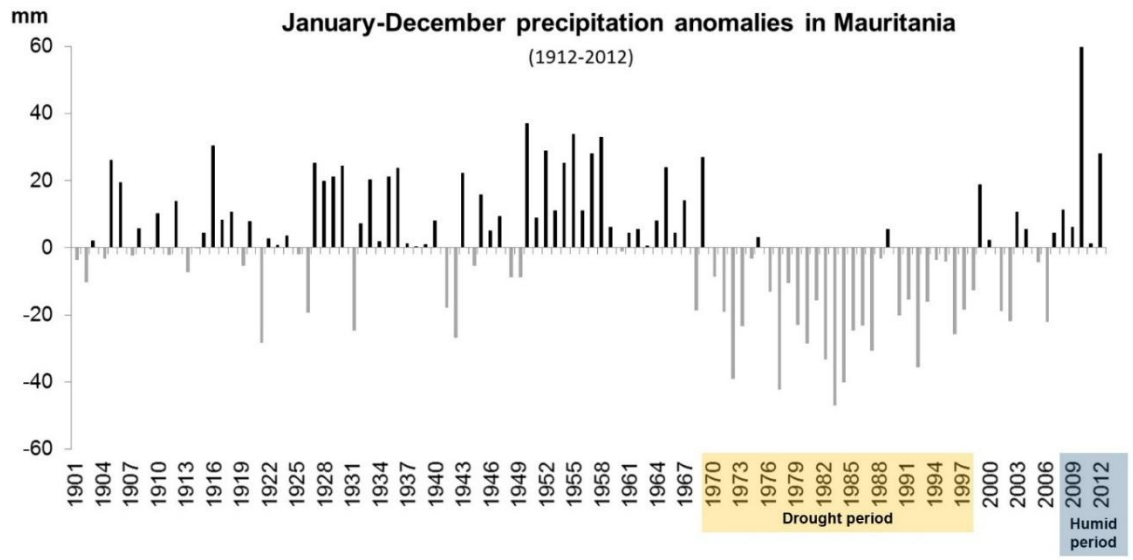

FIG. E.3 - ***Annual precipitation anomalies (mm) in Mauritania between 1912 and 2012. The years of the historical drought in the Sahara-Sahel are demarcated inside the yellow box. The start of the current humid period with considerable increases in precipitation is pinpointed by the blue line. Precipitation data was processed by the Climate Research Unit of University of East Anglia (Jones and Harris 2013) and extracted from the Climate Change Knowledge Portal of the World Bank Group (http://sdwebx.worldbank.org/climateportal/index.cfm).***

References

Jones PD, Harris IC (2013). CRU TS3.21: Climatic Research Unit (CRU) Time-Series (TS) Version 3.21 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901- Dec. 2012). NCAS British Atmospheric Data Centre.

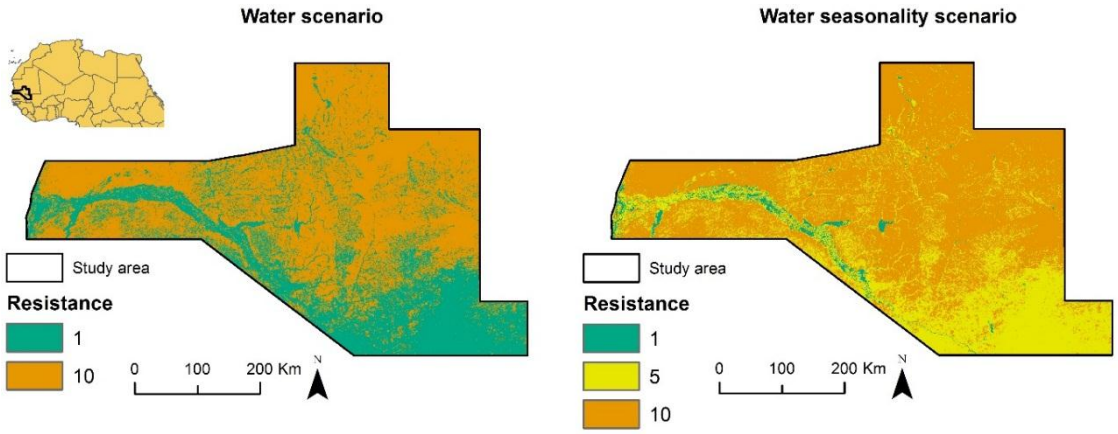

FIG. E.4 - ***Scenarios of landscape resistance used in the landscape connectivity analyses. The two principal scenarios ("Water" and "Water seasonality") were defined for testing the isolation by landscape resistance hypothesis (see Table E.4 in Appendix E). Resistance is coherently symbolized in all scenarios, in which areas of low and high resistance are depicted by greenish and reddish colors, respectively.***

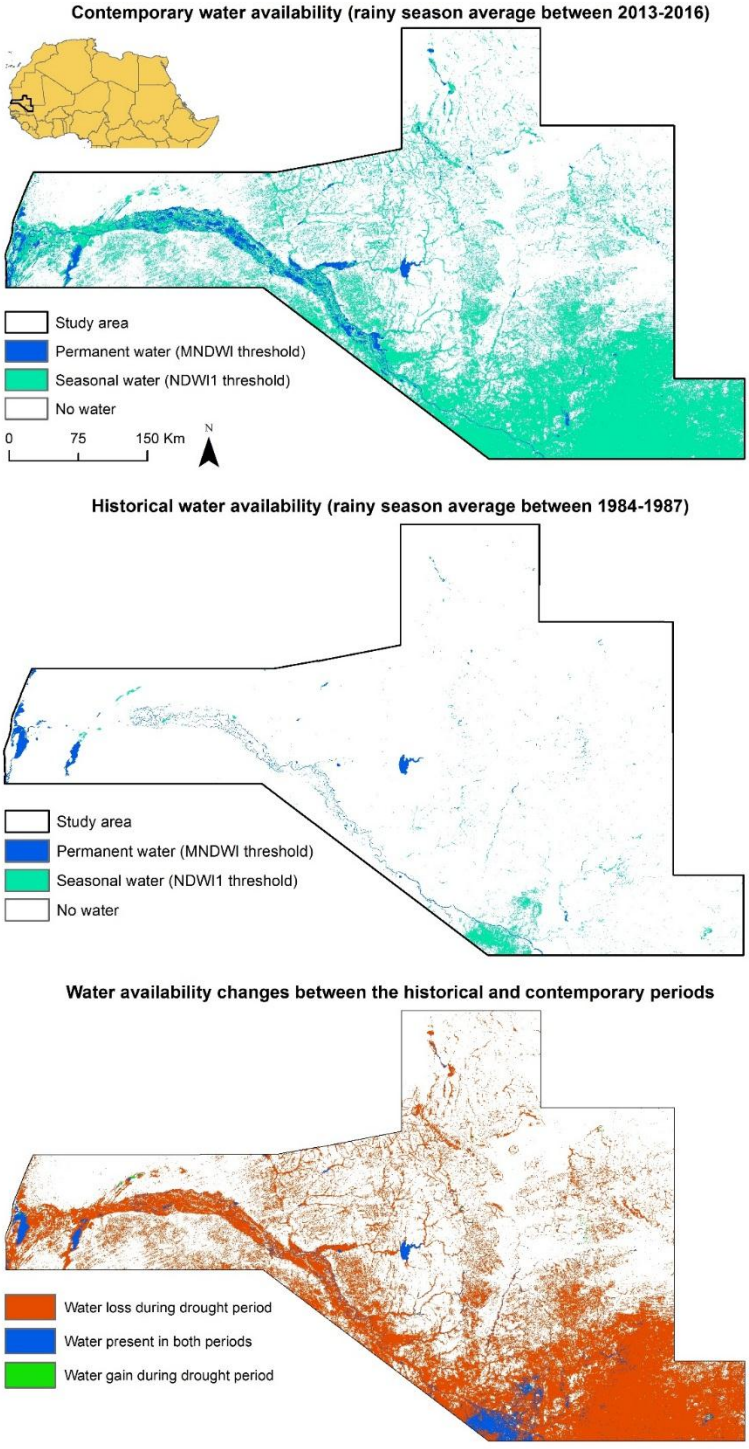

FIG. E.5 - ***Contemporary and historical water availability maps derived from Remote Sensing analyses. The contemporary and historical analyses are based on Landsat image averages for the rainy seasons between 2013-2016 and 1984-1987, respectively. The maps were obtained by applying reclassification thresholds on two water indexes, the Xu's MNDWI (used for permanent water classification; dark blue pixels) and the Gao's NDWI1 (used for seasonal water classification; light blue pixels).***

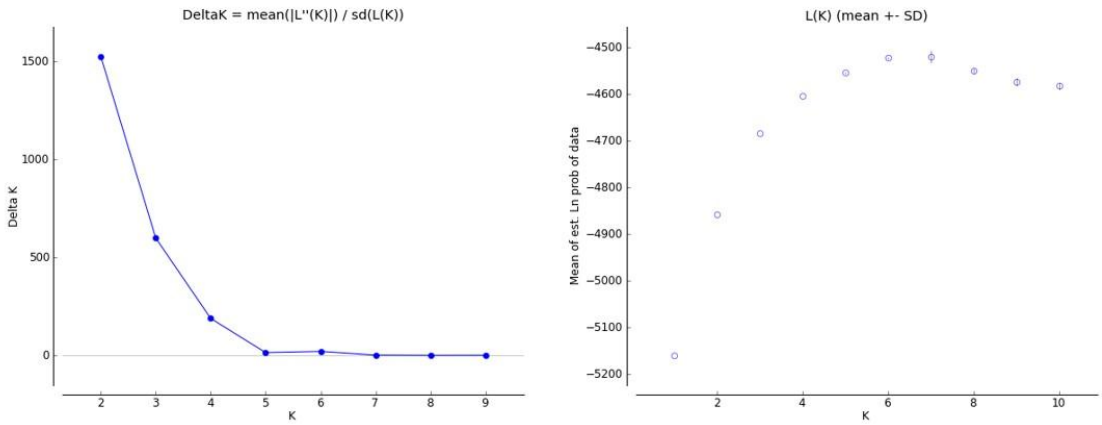

FIG. E.6 - ***Best K-value from the structure analyses of Crocodylus suchus using 12 microsatellite loci dataset. Line plots are indicating the most likely K-value according to the Delta K (left) and L(K) (mean +-SD) (right) methods.***

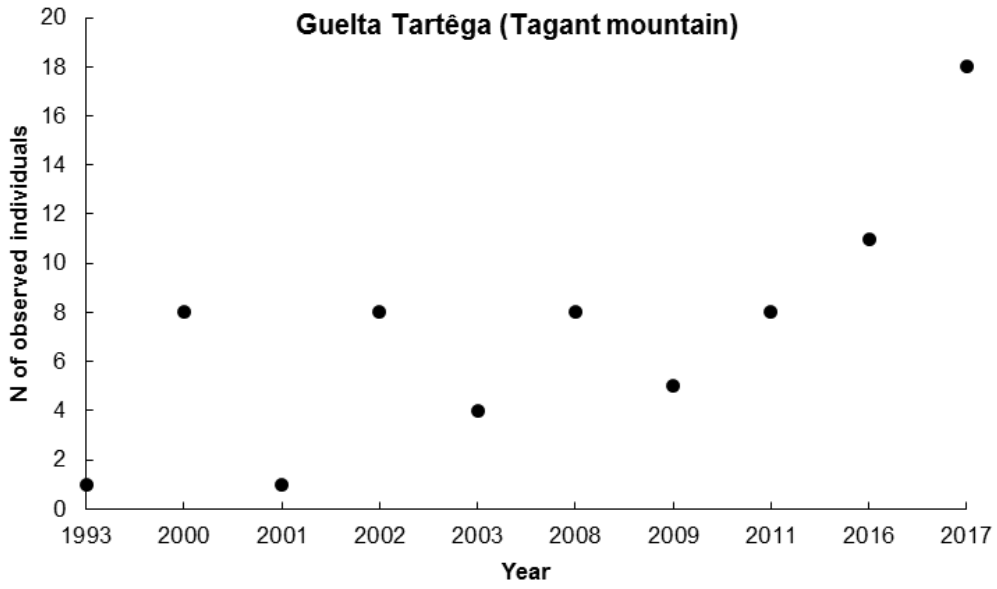

FIG. E.7 - ***Number of observed crocodiles in Guelta Tartêga (Tagant mountain, Mauritania) between 1993 and 2017. Records between 1993 and 2002 were published by Lluch et al. (2004), while records between 2003 and 2017 were obtained during fieldwork expeditions, following methodological procedures described in Brito et al. (2011) and Campos et al. (2016).***

References

Brito, J.C., Martínez-Freiría, F., Sierra, P., Sillero, N., Tarroso P. (2011). Crocodiles in the Sahara Desert: An update of distribution, habitats and population status for conservation planning in Mauritania. PLoS ONE, 6: e14734. doi:10.1371/journal.pone.0014734.

Campos, J.C., Martínez-Freiría, F., Sousa, F.V., Santarém, F., Brito, J.C. (2016). Update of distribution, habitats, population size, and threat factors for the West African crocodile in Mauritania. Amphibia-Reptilia, 37: 325-330.

Lluch, P., Robin, S., Lescure, J. (2004). Le Crocodile du Nil, Crocodylus niloticus Laurenti, 1768 dans le Tagant (Mauritanie). Bull. Soc. Herp. Fr., 111-112: 5-23.

APPENDIX F

Parallel studies

PRELIMINARY ASSESSMENT OF GENETIC DIVERSITY AND POPULATION CONNECTIVITY OF THE MUGGER CROCODILE IN IRAN

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ABSTRACT

The Mugger Crocodile (*Crocodylus palustris*) is a threatened reptile inhabiting the Indian Sub-continent and Western Asia. Despite its “Vulnerable” conservation status, data about population genetic structure and connectivity are unavailable. This study makes a preliminary assessment of the genetic diversity, population structure and habitat connectivity of *C. palustris* in Iran. Ten tissue samples collected along the Sarbaz-Bahukalat basins were analysed and a set of 12 microsatellites was genotyped. Genetic diversity indices were estimated and population substructuring was assessed through Bayesian clustering analysis. Potential connectivity was verified through Remote Sensing water indexes, further implemented in a circuit analysis. Low genetic diversity was observed (mean observed heterozygosity=0.35; mean expected

heterozygosity=0.43) and no population structure was found (K=1). Water index and circuit analysis suggested possible connection among sites. This study highlights the current vulnerability of crocodile populations and the importance of habitat connectivity for their persistence in the arid regions of Iran.

Keywords: Gandou protected area; *Crocodylus palustris*; desert environment; dispersal; genetic diversity; habitat connectivity; population structure.

INTRODUCTION

The Mugger Crocodile (*Crocodylus palustris*) is a threatened species of Western Asia, with an extent of occurrence covering India, Sri Lanka, southern Pakistan, southern Nepal and south-eastern Iran (**Fig. F.1**). Nevertheless, the area of occupancy has continuously declined and local population extinction occurred during the last decades (Cox and Rahman 1994; Van Dink 1993; Whitaker and Andrews 2003). Currently, *C. palustris* populations are fragmented and isolated within protected areas across its distribution, mainly due to continuous habitat destruction and fragmentation for agricultural and industrial expansions during the last decades (Santiapillai and Da Silva 2001). The entanglement and drowning in fishnets, egg collection by humans and illegal poaching for skin, meat and body parts for medicine, represented other major threats that contributed for its populations decline (da Silva and Lenin 2010). The observed declines in abundance, range contractions, decrease of habitat quality and local extirpations have led the Mugger Crocodile to be classified as “Vulnerable” by the IUCN (IUCN 2013), urging the need of a conservation plan for the species and local population monitoring and protection of habitats within protected areas (da Silva and Lenin 2010).

In Iran, *C. palustris* is distributed across an arid region of Sistan-Baluchistan Province, close to the south-western Pakistan border. Crocodiles are mostly found in drainages, large and small dams, and ponds along the Sarbaz-Bahukalat River and its major tributary, the Khaju River (**Fig. F.1**). This region was classified as a protected area in 1971 (Bahukalat protected area) given its importance as a major habitat for crocodiles, being inclusively renamed to Gandou (local name for Mugger crocodile in Iran) protected area years after (Mobaraki 2002). Yet, the situation of *C. palustris* in Iran is

precarious, being nationally classified as endangered. The last survey in 2012 (Mobaraki and Abtin 2013) registered low number of individuals (326 individuals in 80% of its distribution), distributed in small and scattered populations (Mobaraki 2002). These populations are thus vulnerable to demographic, genetic and environmental variability, which may decrease their genetic diversity and increase their extinction risks due to stochastic effects (Frankham 2005). However, dispersal corridors may be formed along major watercourses during the rainy season, which may connect isolated ponds and prompt rescue effects on the small and scattered populations across the Bahukalat basin. Previous studies concerning movement behaviour of *C. palustris* in Iran (Whitaker and Whitaker 1984; Mobaraki and Abtin 2007), confirmed individual dispersal between close and widely separated ponds. The intensive droughts in the region may be associated with movement, since crocodiles may be forced to search for new habitats (Mobaraki and Abtin 2007). Genetic analyses are needed for assessing the diversity and structure of *C. palustris* populations. This study makes a preliminary assessment of the: 1) genetic diversity of *C. palustris* in Iran; 2) population structure across the scattered populations; and 3) possible connectivity between sampled crocodile locations. These data are needed for assessing current population status and for corroborating field observations of possible movements between ponds.

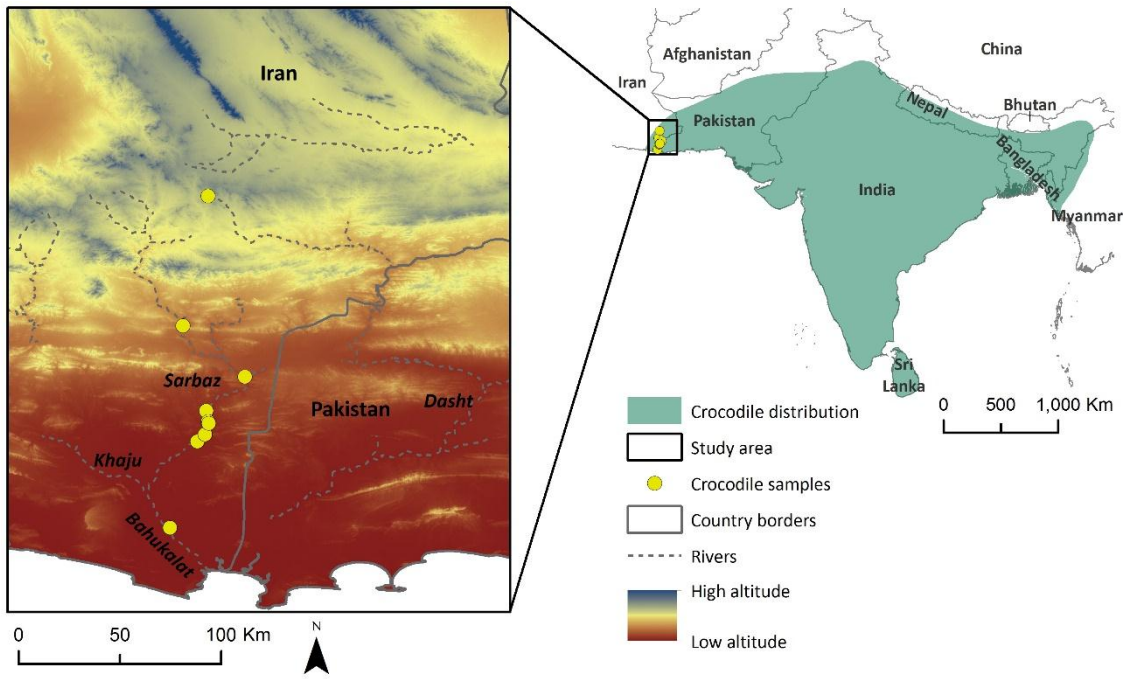

Fig. F.1 - Study area and distribution range of *C. palustris*. The distribution of *C. palustris* (green polygon) was obtained from the IUCN Red List of Threatened Species (http://maps.iucnredlist.org/map.html?id=5667). The zoom displays the current study area, in which the samples of *C. palustris* used in this study are marked in yellow circles. River and country names are written in italics and bold, respectively.

METHODS

Ten tissue samples of *C. palustris* from the Sarbaz-Bahukalat basins were collected from live animals captured along the river margins during past surveys. Tail tips were cut and stored in separate tubes. Samples were kept in 96% ethanol at room temperature until DNA extraction. Total genomic DNA was isolated using the QIAGEN DNeasy Blood & Tissue Kit. A set of 12 nuclear microsatellite loci developed for Crocodylus (FitzSimmons et al. 2001; Miles et al. 2009) were used for genotyping in a single multiplex reaction (**Table F.1**). PCR amplification was performed using the Multiplex PCR Kit (QIAGEN) following manufacturer's instructions in a final 10-µl volume comprising 5ul of Master Mix, 1µM of mix containing forward, reverse and tail primers and approximately 10 ng of DNA. The M13-primer fluorescent labelling protocol (Schuelke 2000) was used with four different dye-labelled tails and forward primer concentration of 1/10 of reverse and tail primers. PCRs were carried out on a BIORAD T100. Samples were amplified using a touchdown profile starting with denaturing at 95ºC for 30s, followed by annealing temperature for 60s and ending with an extension at 72ºC for 45s. The annealing temperature was gradually reduced from 63ºC to 58ºC during 11 cycles, followed by 28 cycles at 58ºC. PCR products were separated by size on an ABI3100xl Genetic Analyser. Allele sizes were scored against the GeneScan-400 LIZ Size Standard, using the GENEMAPPER 4.0 (Applied Biosystems) and manually checked.

Significant deviations from Hardy-Weinberg equilibrium and linkage disequilibrium between pairs of loci were tested using ARLEQUIN 3.5.1.3 (Excoffier and Lischer 2010). The significance tests were performed through a Markov chain method with 1,000 dememorization steps and 10,000 permutations and sequential Bonferroni correction (Rice 1989). Indices of genetic diversity, namely number of alleles per locus (NA), observed (Ho) and expected (He) heterozygosities, and inbreeding coefficient (FIS), were calculated through ARLEQUIN using the 12 loci dataset.

Population structure was assessed by a Bayesian clustering method implemented in STRUCTURE 2.3.4 (Pritchard et al. 2000). The analyses were performed using 10 runs per K-value (number of genetic demes) ranging from 1 to 5, a burn-in period of 100,000 and a run length of 500,000 iterations. The analyses were run based on an admixture model with uncorrelated allele frequencies and without prior information on sample population membership. The most likely K-value was estimated by CLUMPAK (Kopelman et al. 2015) through the Delta K (Evanno et al. 2005) and ln Pr(X|K)

Probability of K (Pritchard et al. 2000) methods. Alignment of cluster membership coefficients from the 5 replicate cluster analyses for each K-value was conducted by CLUMPAK.

Table F.1 - Genetic diversity measures for 12 microsatellite loci of *C. palustris*. Locus code (Locus), fluorescent dyes (Dye), allele range, number of alleles (NA), observed heterozygosity (Ho), expected heterozygosity (He), inbreeding coefficient (FIS) and respective reference of each locus are indicated.

Locus	Dye	Allele range	NA	Ho	He	F_{IS}	Reference
CpDi42	FAM	143-165	7	0.5	0.75	0.35	Miles et al., (2009)
CpP4308	VIC	112	1	-	-	-	Miles et al., (2009)
CpP4311	PET	214-222	3	0.56	0.58	0.05	Miles et al., (2009)
CpDi28	FAM	120	1	-	-	-	Miles et al., (2009)
CpP305	FAM	198-200	2	0.30	0.52	0.44	Miles et al., (2009)
CpP4116	NED	226-230	2	0.20	0.19	-0.06	Miles et al., (2009)
Cj131	FAM	246-250	2	0.67	0.52	-0.30	FitzSimmons et al., (2001)
Cj16	PET	178	1	-	-	-	FitzSimmons et al., (2001)
CUD68	VIC	172-186	2	0.10	0.27	0.64	FitzSimmons et al., (2001)
Cj119	NED	195	1	-	-	-	FitzSimmons et al., (2001)
CpP2504	VIC	346-354	2	0.40	0.52	0.25	Miles et al., (2009)
CpPi29	VIC	251-253	2	0.10	0.10	0.00	Miles et al., (2009)
Total (mean)[1]		8.0	2.75	0.35	0.43	0.19	

Remote sensing (RS) and landscape connectivity analyses were performed to verify possible connections among water habitats across the study area. Satellite images (30x30 m resolution) from Landsat 8 were extracted from the Global Visualization Viewer (http://glovis.usgs.gov/) of the United States Geological Survey (**Table F.2**). Images were selected for covering the rainy season (January-April) in Iran. Only images with less than 10% of cloud cover were used. Two water indexes (WI), the Gao's WI (Gao et al. 1996) and Xu's WI (Xu et al. 2006), were calculated. These

indexes were selected given their good performances in detecting water in arid regions (Campos et al. 2012). Pixels with raw index values were reclassified into a water map using standard thresholds (WI>0=water presence). All RS analyses were conducted in ArcGIS 10.1.

The water map was implemented as a cost surface in a landscape connectivity analysis, using Circuitscape 4.0.5 (McRae 2006). The cost surface was delineated by attributing low (1) and high (10) resistance values for pixels with and without water, respectively. The analysis was run using the water map as unique variable to verify if the sampled crocodile locations were connected through the identified watercourses, rather than identifying potential dispersal corridors for crocodiles.

Table F.2 - Spatial (path and row) and temporal (date) information of Landsat scenes used in this study.

Country	Path	Row	Date	Satellite
Iran	156	42	22-3-2015	Landsat 8
	156	43	22-3-2015	Landsat 8

RESULTS AND DISCUSSION

The 12 loci dataset included four monomorphic loci (CpP4308, CpDi28, Cj16 and Cj119) and loci with low levels of polymorphism (**Table F.1**). Excluding monomorphic loci, the number of alleles per locus varied between two and seven. No locus deviated from Hardy-Weinberg equilibrium after Bonferroni correction and no evidence of linkage disequilibrium was found between any pair of loci. Overall, low values of genetic diversity were observed (mean Ho=0.35 and mean He=0.43), with Cj131 (Ho=0.67; He=0.52) and CpPi29 (Ho=0.10; He=0.10) loci exhibiting the highest and lowest genetic diversity, respectively. The observed levels of heterozygosity in *C. palustris* were low especially when compared with other crocodilian species inhabiting desert environments (Velo-Antón et al. 2014). The analysed populations are located in the western extreme of *C. palustris* distribution, which might explain the observed low genetic diversity. Marginal populations are expected to be more fragmented and have smaller effective population size, suffering from reduced gene flow and stronger effects

of genetic drift relative to geographically central populations (Eckert et al. 2008; Sexton et al. 2009). Additionally, the extreme desert environments in which the Iranian crocodile populations persist might intensify their current geographic isolation and further impact their genetic diversity. The current isolation of crocodile populations is apparently supported by the inbreeding coefficient. A positive FIS value over all loci (FIS=0.19) shows a considerable shortage of heterozygotes compared to Hardy-Weinberg expectations, possibly indicating potential mating among relatives (i.e., inbreeding). However, contrasting values of FIS were also observed among loci (e.g., CUD68=0.64 and Cj131=-0.30), which might be related with effects of low sample size. Caution is required during results interpretation and further fieldwork should be conducted to increase the current number of samples.

The STRUCTURE analyses identified no population structure, with both Delta K and the log of posterior probabilities of K identifying a single genetic group (K=1) as the most probable structure level within the dataset (**Fig. F.2**). The lack of genetic structure may result from different explanations. On one hand, the dataset of microsatellites used in this study was previously selected for *C. suchus* (Velo-Antón et al. 2014) and may not be optimised for detecting such genetic differentiation within *C. palustris*. Expanding the current set of microsatellites by including higher polymorphic loci might improve further measurements of genetic diversity and provide more information on the diversity and structure of *C. palustris* populations. On the other hand, the scattered and supposedly isolated crocodile populations may be able to disperse between ponds along the major streams. This hypothesis is also supported by the RS and circuit analyses (**Fig. F.3**). The WI was capable of identifying courses that possibly connect water habitats across the major basins of the Sarbaz-Bahukalat Rivers. The circuit analyses also attributed high current values to the major watercourses, indicating potential water connectivity among sampled locations.

Crocodilians inhabiting seasonally drying habitats are known to disperse to pools that still contain water (Velo-Antón et al. 2014; Grigg and Krischner 2015), a behaviour that was already recorded in *C. palustris* in Iran (Mobaraki and Abtin 2007). The intensive droughts that characterise the region are probably responsible for this movement behaviour (Mobaraki and Abtin 2010). The results found seem to corroborate field observations concerning the dispersion of *C. palustris*. Possible connectivity between ponds could promote gene flow and the rescue effect of small and isolated crocodile populations, counteracting inbreeding depression, loss of genetic diversity and reduction of adaptive potential (Frankham et al. 2005). Contrarily, decrease in habitat connectivity may permanently isolate crocodile populations, increasing their extinction

risk due to stochastic effects. Two factors may reduce regional habitat connectivity in the future. First, the intensive droughts typical from these regions (Rad et al. 2010) are responsible for seasonally drying the main dispersal streams used by crocodiles. Recent climate change predictions suggest a continuous warming of desert environments (Pal and Eltahir 2015), which may exacerbate the inhospitable conditions presently tolerated by crocodiles. Second, the increasing rate of construction of artificial structures (such as dams; Mobaraki et al. 2013), that may constitute physical barriers to crocodile migration. However, artificial features might also be advantageous by providing suitable water pools for crocodiles even during the dry season. Indeed, the largest crocodile population located in the Sarbaz River is sustained by an artificial lake formed after the construction of the Pishin dam (Rad et al. 2010; Abtin 2012). Future studies should clarify the effects of these features in crocodile dispersal.

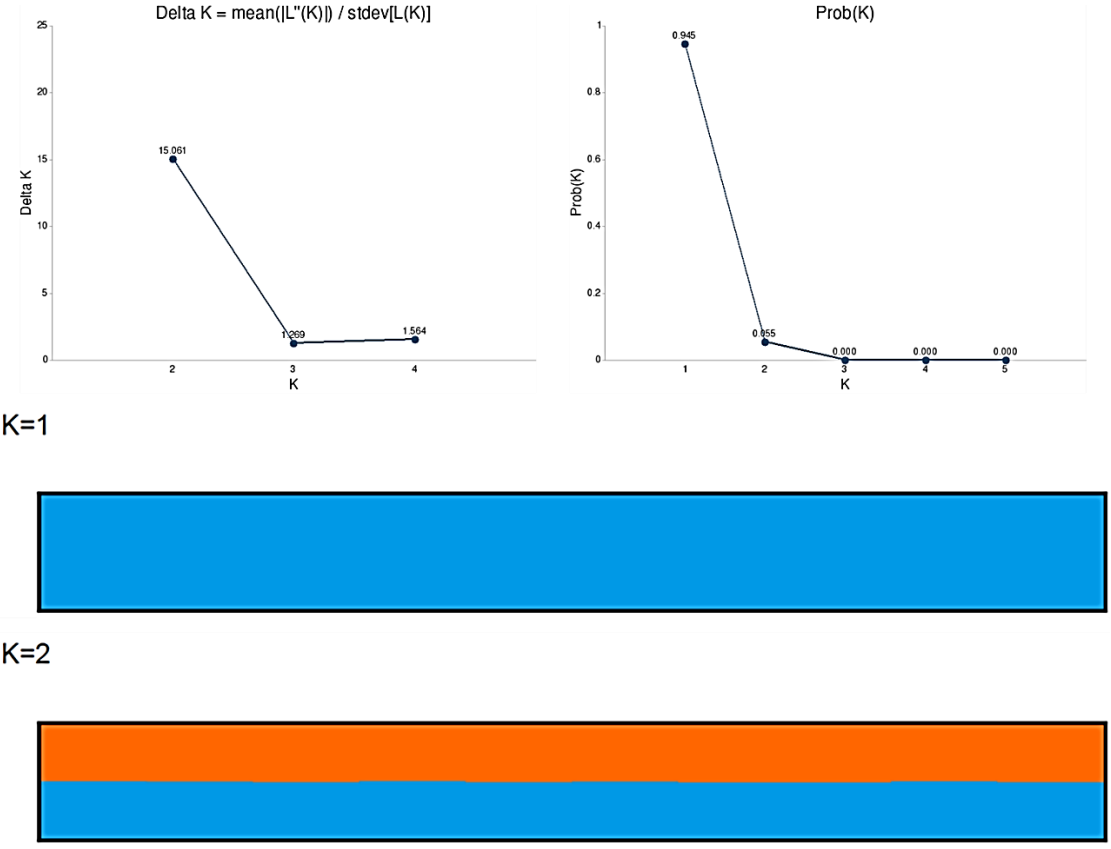

Fig. F.2 - Population structuring analyses of *C. palustris* using 12 microsatellite loci dataset. Line plots are indicating the most likely K-value according to the Delta K (left) and ln Pr(X|K) Probability of K (right) methods. Bar plots show the Bayesian genotype clustering assignment of 10 individuals to one (K=1; upper plot) and two clusters (K=2; lower plot). Different bar colours represent probability of cluster assignment of each individual.

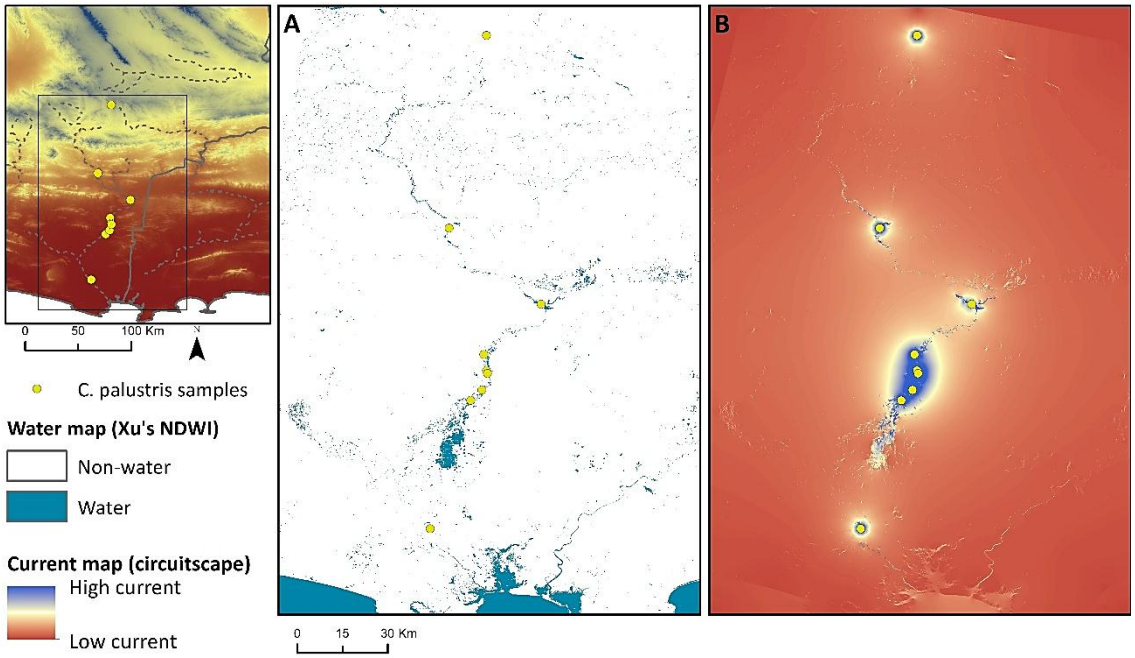

Fig. F.3 - Potential connectivity between crocodile sampled locations. A) Water map derived from Xu's NDWI calculation using Landsat 8 images. B) Circuitscape analysis using the resultant water map as cost surface and showing possible water connectivity between crocodile locations.

This study provided a preliminary assessment about genetic diversity, population structure and connectivity of *C. palustris* in Iran. Still, more information is required to deepen knowledge about the species status in this region. Fieldwork should be conducted along the Bahukalat basin and adjacent tributaries to search for other potential crocodile populations. Satellite telemetry would allow the assessment of crocodile dispersion, increasing the knowledge about their potential dispersal corridors and barriers. Gathering additional data is crucial for updating the regional conservation status of *C. palustris* and to optimise future conservation planning, needed to protect the small and scattered crocodile populations that remain in the arid south-eastern Iran.

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APPENDIX G

List of other publications

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